NATURAL GAS HEATING TECHNOLOGIES: ENERGETIC, ENVIRONMENTAL AND ECONOMIC ANALYSIS OF MODERN LOCAL TECHNOLOGIES IN COMPARISON WITH DISTRICT HEATING

Renato M. Lazzarin – renato@gest.unipd.it
Marco Noro – noro@gest.unipd.it
Department of Management and Engineering, University of Padova – site of Vicenza
stradella S. Nicola, 3 36100 Vicenza (VI) – Italy

Abstract. *Generally, a CHP plant coupled with district heating is considered more efficient than traditional local heating systems from an economic and environmental point of view. This is certainly true for municipal waste CHP plants but for plants fuelled by natural gas the important developments intervened in these last years regarding both boilers (premixed and modulating burners, condensing boilers, etc.), mechanical vapour compression and absorption heat pumps can change the traditional view. At the same time also district heating plants improved. Therefore it is worth to analyse the whole matter comparing advantages and disadvantages of the different alternatives with their wide differentiation among them.*
The paper reports on the analysis of major district heating natural gas based technologies (vapour and gas turbines, internal combustion engine, combined cycles); the cost of the heat power produced in these plants is compared to the cost of producing the same quantity of electrical energy by a reference GTCC- Gas Turbine Combined Cycle (actually the most efficient technology for pure electrical production) and the cost of heat production by modern local heating technologies using natural gas as fuel (condensing boilers, electrical, gas engine and absorption heat pumps). Regarding energy efficiency and polluting emissions, modern local heating turns out to be more efficient than district heating for most CHP technologies. However, it is not the same from the economic point of view, because in Italy natural gas used by cogeneration plants is subjected to a taxation much lower than local heating technologies.

Keywords: District heating, Local heating, Cogeneration, Energy saving

1. INTRODUCTION

The paper reports on the evaluation, from the energetic, environmental and economic point of view, of some urban heating technologies, using natural gas as a fuel. Some of these systems provide for chemical (or electrical) to thermal energy conversion locally:

- ✓ condensing boilers;
- ✓ electrical heat pumps;
- ✓ gas engine heat pumps;
- ✓ absorption heat pumps.

Other technologies provide for combined heat and power (CHP) and district heating (DH). Among these we consider:

- ✓ steam turbines plants;
- ✓ internal combustion engines (ICE);
- ✓ gas turbine combined cycles (GTCC).

Typical efficiencies of these plants are reported in Table 1: the range of the values is quite wide and it requires a parametric study.

We may observe that for all plants working with steam turbines, increasing the thermal output implies a reduction in electrical efficiency. With combined heat and power plants there is the usual problem regarding how to evaluate properly the output: electrical and thermal energy. In this analysis, first of all we consider the electrical efficiency of the best technology for the pure electrical production using natural gas: that is the GTCC, with an electrical efficiency of 55% (actually the best technically achievable). Obviously every cogenerative technology has a lower electrical efficiency: therefore to produce the same electrical energy, CHP plants require more natural gas, producing at the same time some useful thermal energy. The cost, in terms of fuel, to produce this thermal energy can be estimated by the difference between the consumption of natural gas of the two systems. An example allows to explain better the method.

To produce 100 MJ_{el} with a combined cycle whose efficiency is 55% needs 100/0,55=182 MJ_f in terms of natural gas chemical energy. The same electrical energy can be produced by cogeneration with an efficiency, for example, of 40%, thus requiring 100/0,4=250 MJ_f in terms of fuel. The cost of cogenerative thermal production (that may be about 100 MJ_{th} in this example), is 250-182=68 MJ_f.

Table 1. Typical efficiencies (electrical, thermal and total) for the considered technologies (values are expressed in percentage) (Macchi, Consonni, 1995)

	η_{el}	η_{th}	$\eta_I = \eta_{el} + \eta_{th}$
Internal combustion engines (total heat recovery)	25-40	30-45	70-85
Gas turbines	20-38	35-50	70-85
Steam turbines	10-35	60-75	75-90
Gas turbine combined cycles	35-55	10-45	60-85

2. GENERAL HYPOTHESIS

Here are some details for the present analysis:

✓ electrical efficiency of the reference GTCC is 55%, typical value of the most modern power station for pure electrical production based on natural gas (400 MW_{el} size) (Authority, 2002);

✓ both for the reference GTCC and for the combined heat and power plants we have considered the so-called “plant losses” (auxiliaries and voltage transformers, fixed at 5%). Moreover we have to consider the distribution losses of a large central thermoelectric plant that can be evaluated through a distribution efficiency fixed at 95,5% (Authority, 2002). Cogeneration plants have to consider the consumption of electricity for the pumps of the heat distribution system (generally about 1% of the total electrical energy production);

✓ district heating suffers heat losses along the network: obviously these are function of the thermo-vector fluid temperatures, of the degree of insulation of the pipelines and of the network extension; in our analysis we have fixed these losses at 11% of the thermal energy produced by the plants (this is the value in Italy during year 2000, 486 GWh_{th} of losses versus a gross production of 4340 GWh_{th}) (Sacchi, Magnelli, 2002)).

Moreover it is necessary to consider that in DH plants, because of the characteristic of the thermal users (typically residential or service sector heating), the load curve is strongly variable (both during the year and the day); all this makes integrative boilers necessary to satisfy the peaks of thermal request. The production of these boilers is not negligible: in Italy, in year 2000, thermal energy produced by integrative boilers has been about 22% of the total energy distributed by the networks (Sacchi, Magnelli, 2002). This causes a decrease in the plant global efficiency. In our analysis we have fixed at 25% the thermal production by integrative boilers, considering for them a thermal efficiency of 80% that is the normal seasonal efficiency of the installed boilers in DH plants.

In the last years technological developments allowed to build *high seasonal efficiency boilers*. *Condensing boilers* increase further the efficiency (about 10%) by means of sensible and latent heat recovery from the exhaust. Our hypothesis in the present analysis is:

✓ for traditional integrative boilers, having fixed radiation losses at 3% and exhaust losses at 5% with a control efficiency of 87% (Zanardi), a seasonal mean efficiency is given by $(1-(0{,}03+0{,}05))\cdot 0{,}87=0{,}8$;

✓ radiation and exhaust losses for condensing boilers are set at 1% and 2% respectively, giving a control efficiency of 96% so that the seasonal mean efficiency is given by $(1{,}1-(0{,}01+0{,}02))\cdot 0{,}96=1{,}03$.

As far as heat pumps are concerned:

✓ the *Coefficient Of Performance (COP)* is the efficiency index, defined as the ratio between the total useful thermal power and the total inlet power (either electrical or chemical for the motor driving the compressor and for all the auxiliaries);

✓ COP is an index that relates to instant efficiency (full load operation); actually, during stand-by time, some heat pumps auxiliaries (compressor lubricating oil heating, command and control equipment) are on, giving rise to an electrical energy consumption. Furthermore, during start-up phases there are inefficiencies caused by not instantaneous full load operating of the heat pumps; moreover, COP varies with heat pump operating conditions (condensing and evaporating temperatures or air humidity at evaporating coil in air-water or air-air heat pumps). For all these reasons it is the *Seasonal Performance Factor (SPF)* that represents the real efficiency during a whole heating season (ratio between the total thermal energy supplied to the heating plant from the heat pump and the total energy consumed by natural gas and electricity). For the *electrical heat pump* a SPF is assumed of 3, mean value for air-water heat pumps and for 5℃ outside air temperature. For the *gas engine heat pump* heat recovery from engine and from exhaust cooling must be considered. When an i.c. engine (mechanical efficiency 0,3, (Bressanelli, 2000), (Riello, 1999)) is driving the heat pump whose thermodynamic characteristics are similar to the one just considered and useful heat recovered is 80% of the rejected heat, the following three values for the SPF: 1,27, 1,42 e 1,56 relate to COP respectively equal to 2,5, 3 and 3,5. For the *absorption heat pump,* considering that for a single stage machine the maximum theoretic COP is 2, we calculated the SPF taking into account the heat generator seasonal mean efficiency and the auxiliaries consumptions. Varying the first between 60% and 80%[1] and considering the latter 5%[2] of the fuel inlet power (LHV multiplied by mass flow rate), we obtain the following values of SPF:

$$SPF_{absorption}=\frac{Q_c+Q_{ass}}{E_{el,pump}+E_{el,aux}+Q_{gen}/\eta_{gen}}=\frac{2\cdot\eta_{gen}\cdot\dot{m}_{fuel}\cdot LHV}{(1+0{,}05)\cdot(\dot{m}_{fuel}\cdot LHV)}=1{,}1\div 1{,}5$$

where Q_c is the useful heat at the condenser, Q_{ass} at the absorber, Q_{gen} the heat supplied at the generator.

The heat pump shall not be sized on the maximum load: a fraction of the heat demand (in this computation 25%) is satisfied by an auxiliary boiler, for which a seasonal mean efficiency of 90% is assumed (high seasonal mean efficiency boiler).

Anyway, the index that allows an energy comparison of the various systems is the *Primary Energy Ratio (PER)*, that is the useful heat produced per one unit of fuel: for electrical appliances it is given by the product of SPF by electricity generating and distributing efficiencies (respectively 55% and 95,5% for this analysis); for natural gas appliances it is sufficient to take into account these efficiencies when converting electrical energy consumed by auxiliaries into fuel chemical energy. Resulting evaluations are as follows:

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[1] These values take into account also other minor losses (like radiant) and inefficiencies and the partial load operating for the most time of the heating season.

[2] We consider here an air-water gas absorption heat pump.

- 1,58 for electrical heat pumps;
- 1,24, 1,38 and 1,52 for gas engines heat pumps;
- 1,06, 1,25 and 1,44 for absorption heat pumps.

3. ENERGY ANALYSIS

The comparative analysis has been carried out as a function of the electrical production efficiency of the cogenerative technology. For every value of electrical efficiency the thermal fraction was estimated, fixing first principle efficiency between 80% and 90%, depending on the technology (a higher value for steam turbines, lower for gas turbines). Energy costs of CHP plants take into account the distribution and auxiliaries losses and the operation of auxiliary boilers. Horizontal lines in Figure 1 identify the position of condensing boilers and electrical heat pumps; the broken lines strips describe the three COP and the three SPF values considered regarding respectively gas engine and absorption heat pumps. The crossing of the four technologies with horizontal lines indicates on the abscissa a threshold electrical efficiency: when its value is below it that cogenerative technology is less efficient than the correspondent local alternative.

The crossing with the line of condensing boiler gives the following thresholds:

✓ 24% for water steam turbine plants;
✓ 32% for i.c. alternative motor plants;
✓ 39% for gas turbines plants.

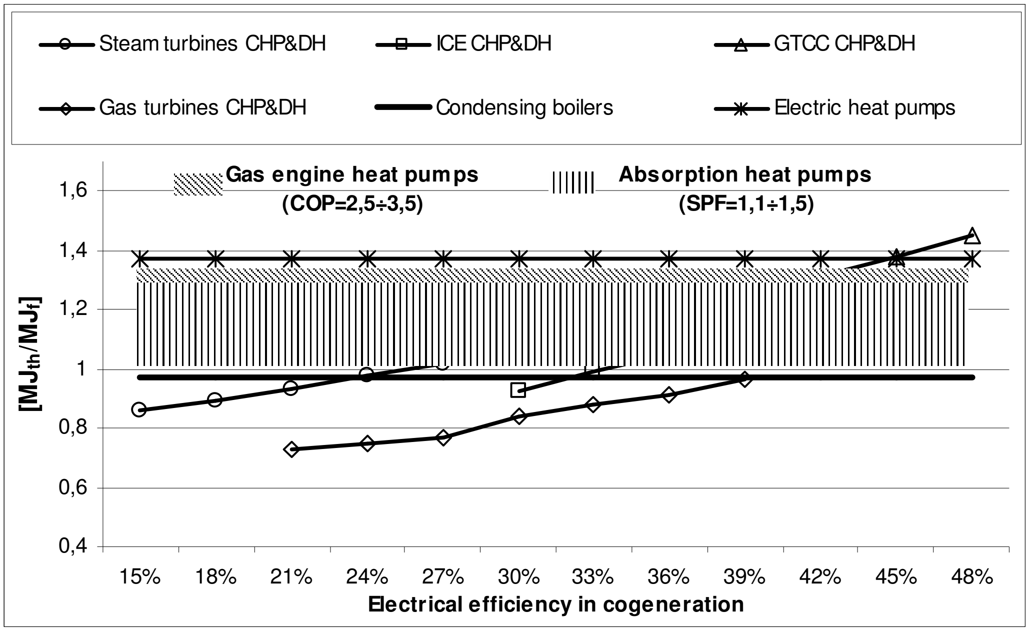

Figure 1. Useful thermal energy to inlet energy ratio (district network and generating plant losses net) in function of electrical efficiencies of the analysed cogeneration technologies.

The 24% of the steam turbine plants seems a low value if one reminds of the 40% efficiency of the large thermoelectric power station. Instead if condensation heat is recovered at a pressure higher than atmospheric, electrical efficiency is generally less than 25% and often less than 20%. Cogeneration by GTCC is always more efficient with respect to condensing boilers. Concerning electrical heat pumps, the only technology that can compete is the GTCC in cogeneration with an electrical efficiency above 45%. District heating by internal combustion engines may result competitive with gas engine heat pumps with COP less than 2,5, lower than the values obtainable with today appliances.

The conclusion of this first analysis is that if the efficiencies just indicated are not exceeded it is better to produce electricity in GTCC power station for pure electric production, favouring high electrical efficiency and producing heat locally by condensing boilers or, better, by gas or electrical heat pumps.

From the energetic point of view, heat pump is the best solution for thermal production, coupled with GTCC power station. In particular, concerning electric heat pumps it is also interesting Figure 2, where the COP_{lim} curve is represented as a function of electrical efficiency of the cogeneration technologies. It is the COP of the electric heat pump that equals the heat production by the particular CHP technology to the heat produced by the surplus of electricity available by a GTCC power station (for pure electricity production) driving an electric heat pump. Taking into account the values of modern air/water heat pumps (COPs varying between 2,5 and 3,6 in nominal conditions, depending on the size and the refrigerant), the conclusion is that, except for combined cycles, cogeneration coupled with district heating is less energy efficient than electrical heat pumps: steam and gas turbines are almost always penalized, while internal combustion engines are competitive only with large size engines and in the case of full load operation (hence with high electrical efficiencies).

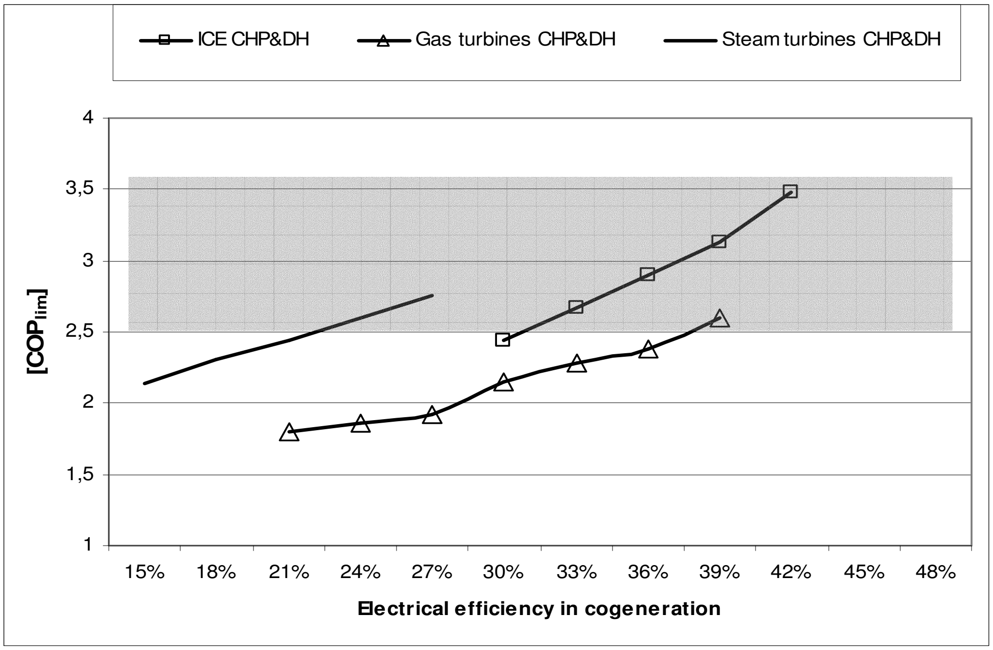

Figure 2. Electric heat pump COP_{lim} that equals the heat production by the particular CHP technology to the heat produced by an electric heat pump (driven by the surplus of electricity available by a GTCC power station for pure electricity production) as a function of the electrical efficiency of CHP systems. The grey strip indicates the COP of modern air/water heat pumps.

4. ENVIRONMENTAL ANALYSIS

Polluting emissions analysis is conducted according to the values reported by technical literature for the various systems.

Pollutants considered are carbon monoxide (CO) and nitrogen oxides (NO_x). All data are reported to a single measure unit, that is mg/kWh_{th} (kWh of useful heat produced), or mg/MJ_{th} (Table 2): this is useful to avoid to refer to the ratio between polluting emission mass and exhaust volume unit, that needs to specify not only exhaust temperature and pressure but also an equal air excess. Table 2 gives polluting emissions range for the various systems. For cogeneration systems a fraction of the total polluting emission equal to the heat rate was attributed to the thermal part. Concerning GTCC for pure electricity production, the value of polluting emission for one unit of electrical energy produced is necessary to quantify electrical heat pumps pollution. Nowadays from the point of view of pollution new condensing boilers with microflame and premixed burners are by far better than the other systems. Because of the unfavourable characteristics of internal combustion engines, district heating by ICE plants, GT plants and gas engine heat pumps are very penalized. To improve the environmental behaviour of the i.c. engines, it is necessary a suitable exhaust treatment: by an oxidant catalyst for CO and eventually reducer for NO_x; anyway it is for now not possible to get the very low emissions of the best burner combustion technologies for small size appliances.

Table 2. Comparison between technologies polluting emissions. Specific values (expressed in mg/MJ_{th} or, more common, in mg/kWh_{th}) have been obtained from literature data ((Di Stefano, 2001), (Jenbacher Energie, 1999), (IEA), (Noro, 2002), (Onza, 1999), (Zanardi)), first converting them to 0% O_2 values, then multiplying them by respective fuel quantities and finally dividing the result by the total net thermal power produced for every technology (these data have been obtained from the previous energetic analysis). The limiting values allowed by today regulations in Italy are reported, (concerning district heating the reference is the "Parere della III Sezione del Consiglio Superiore della Sanità 22/01/97", as well as for gas engine heat pumps, even if for the latter there are not specific standards); for condensing boilers and absorption heat pumps the reference were the limits imposed to obtain the "Blue Angel" mark in Germany

	CO mg/kWh_{th} (mg/MJ_{th}) Typical emission values		NO_x mg/kWh_{th} (mg/MJ_{th}) Typical emission values	
	from	to	from	to
Steam turbine CHP & DH	68 (19)	136 (38)	161 (45)	560 (156)
Limit	168 (47)		367 (102)	
Internal combustion engines CHP & DH	872 (242)	1849 (514)	1171 (325)	2330 (647)
Limit	297 (83)		731 (203)	
GTCC CHP & DH	118 (33)	350 (97)	405 (112)	986 (274)
Limit	79 (22)		105 (29)	
Gas turbine CHP & DH	54 (15)	158 (44)	195 (54)	461 (128)
Limit	195 (54)		260 (72)	
Condensing boiler	7 (2)	21 (6)	11 (3)	34 (10)
Limit	101 (28)		178 (50)	
Electrical heat pump	28 (8)	68 (19)	170 (47)	308 (86)
Gas engine heat pump	537 (149)	669 (186)	416 (116)	589 (164)
Limit	285 (79)		702 (195)	
Absorption heat pump	40 (11)	79 (22)	168 (47)	289 (168)
Limit	101 (28)		178 (50)	

Concerning CO_2 emissions, Figure 3 reports the specific values calculated as follow:

$$\frac{2{,}75\left[\frac{kg_{CO_2}}{kg_{CH_4}}\right]\cdot 0{,}7139\left[\frac{kg_{CH_4}}{Nm^3{}_{CH_4}}\right]}{9{,}6\left[\frac{kWh_{CH_4}}{Nm^3{}_{CH_4}}\right]}\cdot\left(\frac{(1-\alpha)}{3{,}6\left[\frac{MJ_{CH_4}}{kWh_{CH_4}}\right]\cdot PER\left[\frac{MJ_{th}}{MJ_{CH_4}}\right]}+\frac{\alpha}{3{,}6\left[\frac{MJ_{CH_4}}{kWh_{CH_4}}\right]\cdot\eta_{boiler}\left[\frac{MJ_{th}}{MJ_{CH_4}}\right]}\right)$$

The 2,75 factor is got by the stoichiometric CH_4 burning equation; for local heating technologies (except condensing boilers) it has been taken into account the load supplied by integrative boilers as described before by mean of the α factor (for cogeneration plants α=0 because the contribution of integrative boilers is included in PER). Finally, for electric heat pumps the first term is replaced by $(1-\alpha)\cdot(0{,}5\div 0{,}7)\left[\frac{kg_{CO_2}}{kWh_{el}}\right]\Big/\left(3{,}6\left[\frac{MJ_{el}}{kWh_{el}}\right]\cdot SPF\left[\frac{MJ_{th}}{MJ_{el}}\right]\right)$, in which the CO_2 specific emission has been varied between 0,5 and 0,7 kg_{CO2}/kWh_{el} (the first correspond to the european thermoelectric power stations mean, the second to the italian one). CO_2 emissions in Figure 3 are depicted by broken lines strips because of the COP and SPF ranges mentioned before.

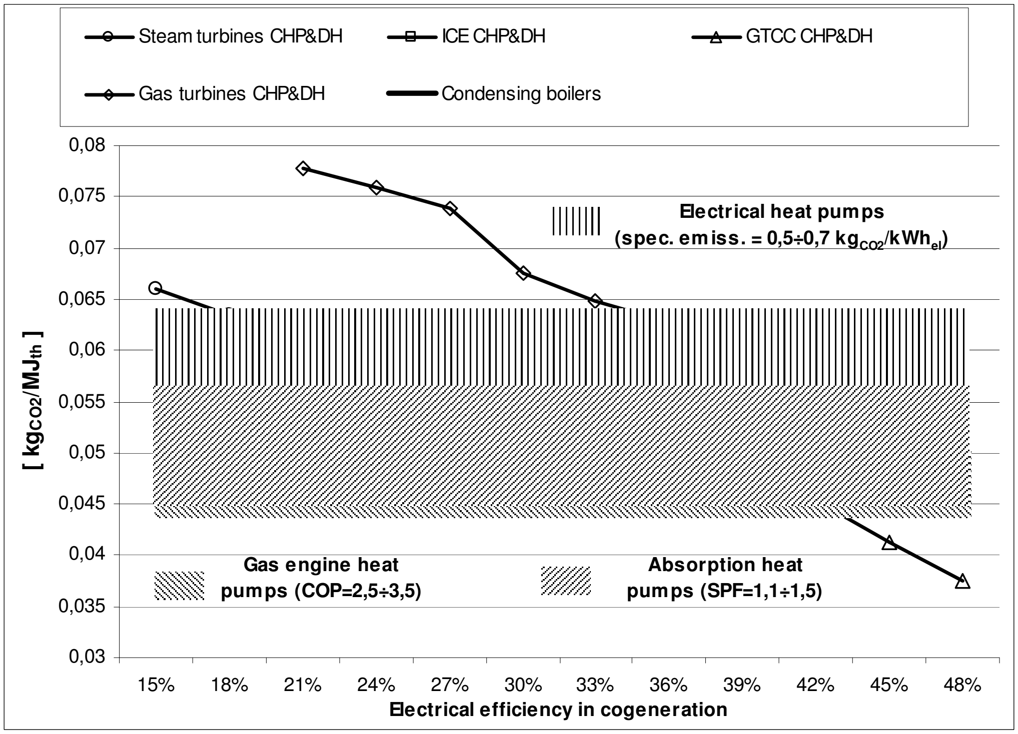

Figure 3. CO_2 emissions per unit of useful thermal energy.

Only GTCCs are better than local heating technologies; gas engine and absorption heat pumps provide the best performances, while ICE CHP&DH plants are competitive with these and better than condensing boilers if the efficiency is higher than 36%. Electrical heat pumps performances are strongly dependent on electrical energy generation efficiency of power stations.

5. ECONOMIC ANALYSIS

Finally the various alternatives were compared from the point of view of costs, considering the heating of a school and office building. The hypothesis are summarised in Table 3. Some details are necessary:

✓ Investment costs of the heating appliances were estimated starting from the nominal capacity of the heating appliances.

✓ Appliances investment costs have been obtained by suppliers' price lists, while plant investment costs by builders' data. Reference sizes of the plants for the investment costs calculations are taken from some real plants in the north of Italy. Reference heat distribution networks are 20 km long for the GTCC and gas turbine plants and 12 km long for the ICE plant.

✓ Ordinary maintenance and personnel costs have to be considered in calculating the cost of the useful thermal energy unit. Reported data have been derived from communications with people in charge of the plants and from direct experience of the authors. In particular, a twelve people staff in three shifts was supposed (each eight hours long), with contemporary presence of two people.

✓ Fuel cost is one of the most important item and it is strongly variable particularly due to taxation which is extremely different for cogeneration with respect to local heating. This favourable treatment for CHP plants is commonly justified by the higher efficiency and smaller environmental impact of these technologies. As in the present paper an equivalence or even a better behaviour of modern local heating systems was demonstrated, the economic comparison was carried out both with and without fiscal benefits. This means operating both with market prices and with a same natural gas cost for all the systems.

Table 3. Economic analysis data for the various alternatives

	ICE CHP & district heating	GTCC CHP & district heating	Gas turbine CHP & district heating	Condensing boiler	Gas engine heat pump	Electrical heat pump	Absorption heat pump
Nominal power	4,66 MW_{el}	31 MW_{el}	21,2 MW_{el}	760 kW_{th}	380 kW_{th} (285 kW_{th} integr. boiler)	140 kW_{el} (285 kW_{th} integr. boiler)	380 kW_{th} (285 kW_{th} integr. boiler)
Appliance or plant investm. cost	650 €/kW_{el}	1250 €/kW_{el}	850 €/kW_{el}	75 €/kW_{th}	250 €/kW_{th} (50 €/kW_{th} integr. boiler)	500 €/kW_{el} (50 €/kW_{th} integr. boiler)	250 €/kW_{th} (50 €/kW_{th} integr. boiler)
Heat network investm. cost	550000 €/km	550000 €/km	550000 €/km	-	-	-	-
Fuel cost (taxes and fiscal reduct. included)	0,25 €/Nm^3	0,25 €/Nm^3	0,25 €/Nm^3	0,5 €/Nm^3 (0,25 €/Nm^3)	0,5 €/Nm^3 (0,25 €/Nm^3)	0,5 €/Nm^3 (0,25 €/Nm^3)	0,5 €/Nm^3 (0,25 €/Nm^3)
Ordinary maintenance cost	0,01033 €/kWh_{el}	0,8% of the plant investment cost	0,8% of the plant investment cost	3,5 €/(kW_{th} year)	5 €/(kW_{th} year)	10 €/(kW_{el} year)	3,5 €/(kW_{th} year)
Personnel cost	37000 €/(person year)	37000 €/(person year)	37000 €/(person year)	-	-	-	-

Figures 4 and 5 report the results concerning the cost of the useful thermal energy unit. In Figure 4 the market prices (with the tax burden) of natural gas are considered, while in Figure 5 all technologies are considered at the same cost of natural gas. *The solutions most advantageous are gas turbines technologies, in particular combined cycles*. District heating by ICE is cheaper than condensing boilers, absorption and gas engine heat pumps only because of natural gas fiscal burden on the latter, as it is easy to perceive comparing the two figures. Selling price of the useful thermal unit by CHP and district heating companies, variable on the base of the users from 0,05 €/kWh$_{th}$ (hotels for example) to 0,1 €/kWh$_{th}$ (residential heating), is comparable with condensing boilers, absorption and gas engine heat pumps, but even with the tax burden local heating technologies can present a cheaper bill in residential heating. Electrical heat pumps instead are disadvantaged, by the high cost of electricity (that in Italy is the highest in Europe). Maybe their summer use can justify their utilization.

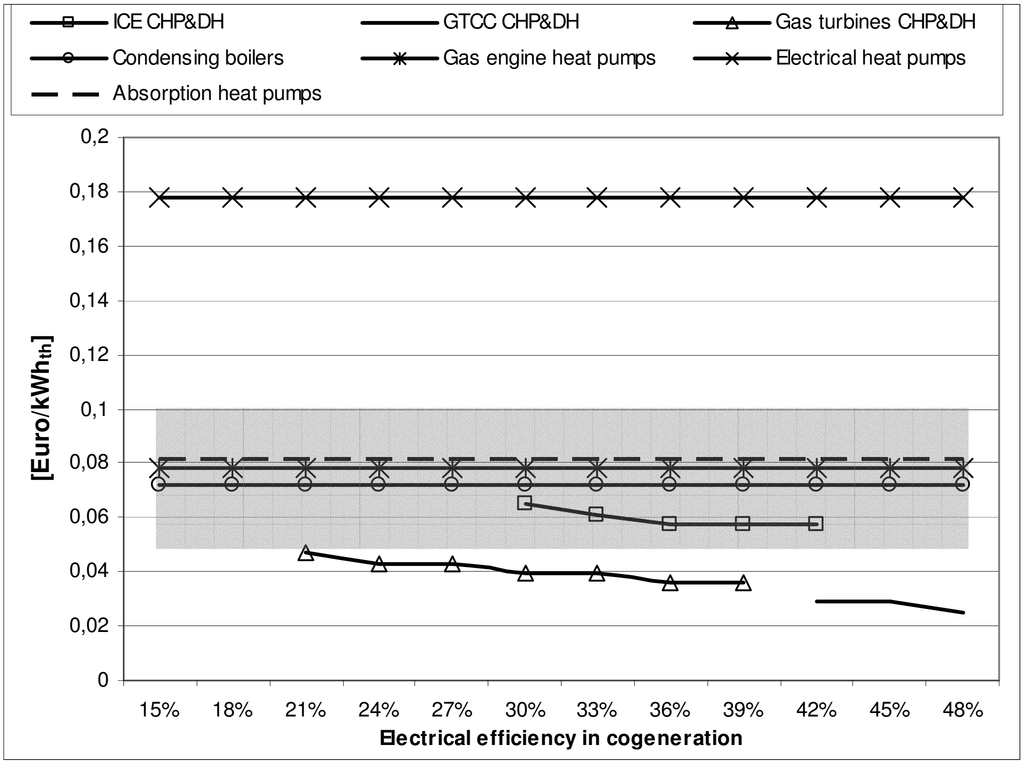

Figure 4. Cost of the useful heat unit for the various technologies (analysis at market prices of natural gas). The values have been calculated summing the costs in Table 3, spreading them on fifteen years of useful life with a 5% reference rate; in particular, fuel costs for local heating technologies have been calculated on the base of their PER, while the CHP technologies costs on the base of electricity and heat production data of the reference DH plants ((AGSM), (Onza, 1999)) and of the results depicted in Figure 1. For the gas engine heat pump, we have assumed a COP of 3. The curves are drawn in function of electrical efficiency of the cogeneration technologies; in the grey strip we have reported the price of the kWh$_{th}$ of one of the company managing district heating plants in the north of Italy.

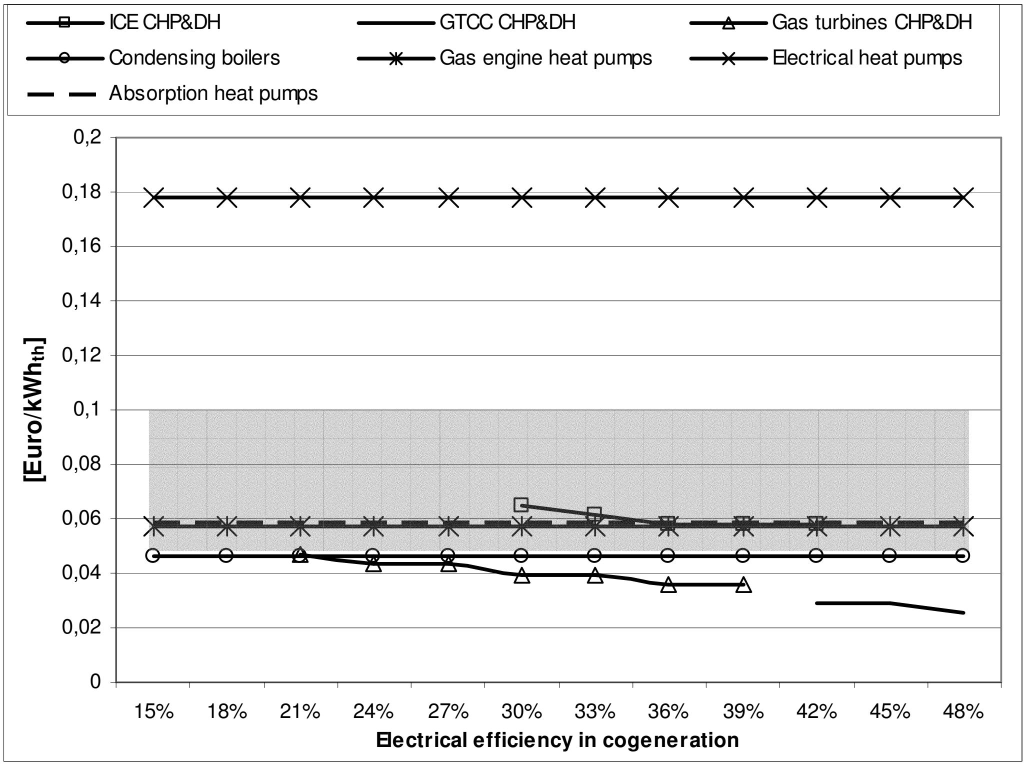

Figure 5. As Figure 4 with cost of natural gas of local heating equals to the CHP&DH plants one (0,25 €/Nm^3).

6. CONCLUSIONS

District heating is often less efficient with respect to modern heating technologies using natural gas. Condensing boilers guarantee higher efficiencies with respect to “traditional” district heating (steam and gas turbines plants), while only last generation combined cycles can give better results than heat pumps.

Comparison on the base of polluting emissions is maybe more surprising: because of the recent technological improvements of burners (low-NO_x, modulating and premixed burners), their use produces by far a lower environmental impact with respect to CHP technologies (combined cycles included). To get over this important gap, cogeneration plants must be equipped with pollutants treatment and reduction systems before exhaust release much more effective than the actual.

The comparison is less favourable to modern local heating technologies from the economic point of view, essentially because of the very different fiscal burden which favours strongly district heating systems. Reasons for this public help should be reconsidered on the basis of the new technological development of local heating systems.

The conclusion of this paper is that district heating cannot be considered the most efficient system available for producing heat and power: this is true for municipal waste plants. But when using natural gas as fuel, CHP systems are really the best only when the most efficient technologies (GTCC) are employed.

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