CO-AND TRI-GENERATION ENVIRONMENTAL IMPACT

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ABSTRACT: *The conditions for co-and tri-generation to reduce CO_2 emissions are discussed as well the global impact of these techniques if they were extensively used. CO_2 emissions saving will depend on the CO_2 emissions of the electricity from the network. Saving as high as 15% can be foreseen. Moreover, if biofuels are to be used, saving will be much more important.*

RESUME: *Les conditions pour que la co-et tri-génération réduisent les émissions de CO_2 ainsi que l'impact planétaire de ces techniques sont discutés. Les économies d'émissions de CO_2 dépendent des émissions de CO_2 associées à la production d'électricité du réseau. Des économies pouvant atteindre 15% sont envisageables. De plus, si des biocarburants sont utilisés, les économies seraient encore beaucoup plus importantes*

As long as global warming is a big concern, Combined Heat Cooling and Power units which yield first law efficiencies much higher than conventional power stations look attractive. However, it is important to know how effective those systems are. Two questions are raised :

- what are the conditions for cogeneration and trigeneration to reduce CO_2 emissions?
- If such techniques were extensively used, how many CO_2 emissions could be saved and the effect would it be significant?

Those are the two questions addressed in this paper.

The idea for the use of combined heat and power is very simple : it comes from the verification that in a conventional power station a large amount of heat is rejected (the amount of electricity produced and heat rejected are generally close). Moreover heat and electricity consumption are also of the same order of magnitude, they represent, at a national level, each about 1/3 of the consumed energy.
From those two verifications, one could reasonably expect that the energy production should be organized in such a way so as to satisfy the needs for electricity and heat from the same energy production system.
However, this is not the case since, on one hand, electricity is generally produced in highly centralized power stations and distributed through networks. On the other hand, heat is generally produced at the end user location when the fuel is distributed through a network.
The concept of cogeneration is well known in this conference but let me insist on one specific point. In general, in cogeneration plants, the unit size matches the heat demand rather than the electricity demand. That means that electricity is, as a matter of fact, a by-product of heat. It is not possible to organize all the energy production so that all the electricity and all the heat are produced from the same units. The reasons being that the peaks do not coincide. There will, probably, always exist power stations to produce only electricity. However, there exists a possibility that a large amount of heat and chilling be produced by cogeneration and trigeneration. As an illustration, in this paper, we shall consider only the uses for space heating and air conditioning which represent a large amount of thermal energy consumption.
The questions I want to address here are: what would be the environmental impact if heat, chilling and electricity would be produced, at a much larger scale, from combined heat and power units? Can cogeneration and trigeneration be important techniques for an energy strategy which would preserve environment and allow for energy consumption increase?

1. The conditions for cogeneration units to be environmentally friendly

Cogeneration and trigeneration units always yield higher global efficiencies than power stations. However, their environmental impact is not always better, it depends on the local electric supply environmental impact. Let us consider first the conditions for cogeneration units to be environmentally friendly.
The cogeneration unit produces electrical energy (W), useful heat (Q) out from primary energy Q_p with ratios:

$$\begin{cases} \eta_{el} = \dfrac{W}{Q_P} \\ \eta_g = \dfrac{W+Q}{Q_P} \end{cases}$$

The environmental impact with respect to CO_2 emissions is given :

$$E_{cog} = Q_P \times A_f$$

where E_{cog} is the CO_2 emission from the cogeneration unit corresponding to Q_p and A_f is the CO_2 emission per kWh of fuel. If W and Q were produced by conventional means: W from the electric network and Q from a burner with an efficiency η_b, the CO_2 emission would be:

$$E_{conv} = W \times A_{el} + \frac{Q}{\eta_b} \times A_f$$

where E_{conv} is the CO_2 emission from the conventional means to get W and Q and A_{el} is the CO_2 emission per kWh of electricity.
The ratio between the conventional and cogeneration CO_2 emissions is:

$$R = \frac{E_{conv}}{E_{cog}} = \frac{W \times A_{el} + \frac{Q}{\eta_b} \times A_f}{Q_P \times A_f} = \qquad [1]$$

$$\eta_{el} \frac{A_{el}}{A_f} + \frac{\eta_g - \eta_{el}}{\eta_b}$$

The condition for cogeneration to be environmentally friendly is R>1 which yields:

$$R = \eta_{el} \frac{A_{el}}{A_f} + \frac{\eta_g - \eta_{el}}{\eta_b} > 1 \qquad [2]$$

$$\Rightarrow \frac{A_{el}}{A_f} > \frac{1}{\eta_{el}} - \frac{\eta_g - \eta_{el}}{\eta_b \times \eta_{el}} \qquad [3]$$

The ratios η_g and η_{el} depend on the cogeneration technology. The conditions for inequation [2] to be fulfilled depend on the cogeneration ratios and on the national electricity production environmental impact. In the following, four examples corresponding to different η_{el} will be considered; with the present technology, those four cases correspond more or less to steam turbine (S.T.), gas turbine (G.T.), diesel (or gas) engine (G.E.) and combined cycle (C.C.). Table I shows the results for η_b=0.9 and $A_{el}/A_{el} = 3$ (A_{el}=0.6 and A_f=0.2 $kgCO_2/kWh_{N.G.}$). The CO_2 saving due to cogeneration is equal to ($1\text{-}R^{-1}$). It is shown on Figure I for three values of A_{el}/A_f and for two values of η_g as a function of η_{el}.
Note that the trend is that the CO_2 saving increases with A_{el}/A_f, η_{el} as well with η_g. From inequation [3] as well as from Fig.I, one can see that there exists a minimum value for A_{el}/A_f below which cogeneration is not environmentally friendly. Taking η_b=0.9; η_g=0.7 and η_{el}=0.3 yields:

$$\frac{A_{el}}{A_f} > 1.85 .$$

Table I: CO_2 emissions saving ($1\text{-}R^{-1}$) due to cogeneration for $A_{el}/A_f = 3$

	η_{el}	η_g	R	$1\text{-}R^{-1}$
Case 1 S.T.	0.15	0.75	1.11	10%
Case 2 G.T.	0.3	0.7	1.34	25%
Case 3 G.E.	0.4	0.75	1.58	37%
Case 4 C.C.	0.5	0.8	1.83	45%

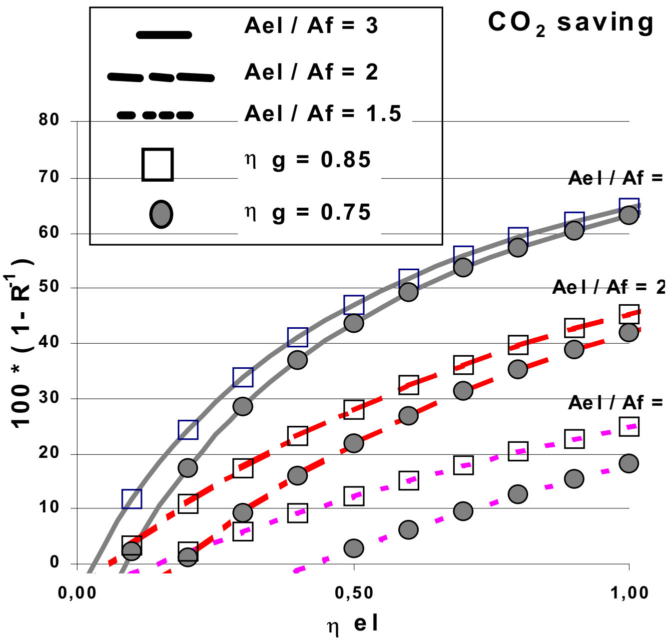

Figure 1: CO_2 saving versus η_{el} for the cogeneration

In a country like France where $A_{el}/A_f \approx 0.5$ this explains why cogeneration is not competitive with nuclear electricity; it is only competitive with fossil fuel auxiliary power stations.

Several conclusions can be drawn from Table I and Figure I:

1. Cogeneration is highly effective when the ratio A_{el}/A_f is high. That corresponds to countries in which the power stations have low efficiency or to auxiliary power stations used during peak hours. Important CO_2 emissions reduction ranging from 25 to 45% are possible using well suited cogeneration plants. That means also that the substitution of obsolete power stations (which will occur in the next future) by efficient cogeneration plants can highly contribute to CO_2 emissions saving. This will be all the more important in countries where the electricity generation is at high CO_2 emission level. But, even in France, the substitution of obsolete auxiliary power stations by efficient cogeneration plants can contribute to CO_2 emission saving.

2. As the trend is towards higher efficiencies for power stations, that means that, in a long term, cogeneration units will also have to improve their figures of merit to remain competitive

3. Cogeneration is not environmentally friendly when electricity is produced from renewable or nuclear energy. In countries where this occurs, priority must be given to renewable and nuclear electricity and cogeneration must be used only as a substitution to fossil fuel power stations.

4. A specific case when cogeneration is the most environmentally friendly is when biofuels (biogas, wastes, etc.) are used. In that peculiar case, not only, the unit does not contribute to global warming but it can be a CO_2 sink.

2. The conditions for trigeneration units to be environmentally friendly

Cogeneration is very well suited to space heating but, in moderate climates, the needs for space heating exist only in winter. However summer air conditioning (A.C.) which is already highly disseminated in developed countries like USA, Japan, Israel, etc. is under rapid development in lots of countries like Europe and emerging countries. The problem is that, in most climates, the energy consumption due to air conditioning in summer is much higher than that due to heating in winter. Moreover, AC uses often electric driven chillers. The consequence is that this high energy consumption involves electric peak demands in summer and it may unbalance the electric network as it was the case recently in California. Therefore, there are two reasons in favor of trigeneration: the first one is to relieve the electric network when the demand is very high due to A.C., the second one is to reduce CO_2 emissions. Let us analyze the CO_2 emissions balance in the case of trigeneration. The case study considered is one when an absorption unit (using a refrigerant with GWP=0) is used with a cogeneration unit. The cogeneration unit is designed so as to match the cooling demand. For simplicity, we assume here that no heat is used.

The trigeneration unit produces electrical energy (W), heat (Q) used for cooling (C) out from primary energy Q_p with ratios:

$$\begin{cases} \eta_{el} = \dfrac{W}{Q_P} \\ \eta_g = \dfrac{W+Q}{Q_P} \\ \eta_g^c = \dfrac{W+C}{Q_P} = \dfrac{W+Q\times COP_{abs}}{Q_P} = \\ \eta_g + (\eta_g - \eta_{el})(COP_{abs}-1) \\ COP_{abs} = \dfrac{C}{Q} \end{cases}$$

where η_g *and* η_g^c are the global efficiencies considering respectively the useful heat Q or the chilling effect C and COP_{abs} is the absorption chiller COP.

The only emissions for the trigeneration come from the fuel so that the environmental impact with respect to CO_2 emissions is still given by:

$$E_{trig} = Q_P \times A_f$$

If W and C were produced by conventional means: W from the electric network and C from a vapor compression chiller fired with electricity with a COP equal to COP_{comp}, the indirect CO_2 emission due to energy consumption only would be:

$$E_{conv}^{ind} = W \times A_{el} + \frac{C}{COP_{comp}} \times A_{el}$$

where E_{conv}^{ind} is the CO_2 emission, due only to energy consumption, from the conventional means to get W and C and $COP_{comp} = \dfrac{C}{W_{comp}}$ is the COP of the electric chiller.

At this indirect CO_2 emission, it would be necessary to add the direct emission due to the refrigerant leakage:

$$E_{conv}^{dir} = M \times \tau \times GWP$$

where M is the refrigerant mass in the chiller, τ is the leakage rate and GWP is the refrigerant Global Warming Potential. The GWP is high (about 1500kg CO_2 per kg of refrigerant) and the leakage rate can be high (10% or more) so that this contribution may eventually be important. However, the trend in the new compact chillers is to reduce drastically the leakage rate (less than 1%) so that the direct contribution is small.

The ratio between the indirect conventional and trigeneration CO_2 emissions is:

$$R_C^{ind} = \frac{E_{con}^{ind}}{E_{cog}} = \frac{W \times A_{el} + \dfrac{C}{COP_{comp}} \times A_{el}}{Q_P \times A_f} = \eta_{el}\frac{A_{el}}{A_f} + \frac{C}{COP_{comp} \times Q_P}\frac{A_{el}}{A_f} \quad [4]$$

Introducing η_g *and* $\beta = \dfrac{COP_{abs}}{COP_{comp}}$, we get:

$$R_C^{ind} = \left[\eta_{el} + \beta\left(\eta_g - \eta_{el}\right)\right]\frac{A_{el}}{A_f} \quad [5]$$

For the total emissions including direct emissions due to refrigerant leakage, we get:

$$R_C = \left[\eta_{el} + \beta\left(\eta_g - \eta_{el}\right)\right]\frac{A_{el}}{A_f} + R_C^{dir}$$

The condition for trigeneration to be environmentally friendly is $R_C>1$ and this condition will be systematically satisfied if $R_C^{ind} > 1$ which yields:

$$R_C^{ind} = \left[\eta_{el} + \beta \times \left(\eta_g - \eta_{el}\right)\right]\frac{A_{el}}{A_f} > 1 \quad [6]$$

$$\Rightarrow \frac{A_{el}}{A_f} > \frac{1}{\eta_{el} + \beta \times \left(\eta_g - \eta_{el}\right)} \quad [7]$$

Table II shows the results for $A_{el}/A_f = 3$ and β=0.4 (COP_{abs}=1.2 and COP_{comp}=3):

Table II: CO_2 emissions saving ($1-R^{-1}$) due to trigeneration

	η_{el}	η_g	R_C	$1-R_C^{-1}$
Case 1 S.T.	0.15	0.75	1.17	15%
Case 2 G.T.	0.3	0.7	1.38	27%
Case 3 G.E.	0.4	0.75	1.62	38%
Case 4 C.C.	0.5	0.8	1.86	46%

Figure 2 displays the results of the CO_2 saving for the same values of A_{el}/A_f and η_g as in Figure I.

The results and the conclusions which can be drawn are very similar for trigeneration and cogeneration. Trigeneration can be favorably used to relief the electrical network, it will highly decrease the CO_2 emissions if an appropriate cogeneration unit is used. The CO_2 abatement could still be higher if a higher cooling COP (COP=1.5) was achieved with a triple effect absorption unit.

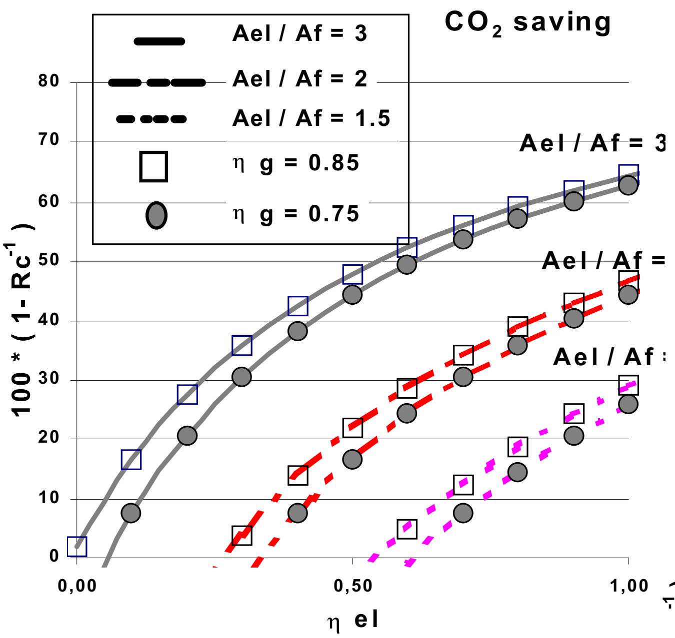

Figure 2: CO_2 saving versus η_{el} for the trigeneration

Two promising cases to be developed

Other interesting products would deserve to be developed. The first one is a reversible sorption heat pump and the second one is a total energy system.

1.1 <u>Reversible Heat Pump</u>

In winter, the heat from the cogeneration unit could be used to fire a sorption heat pump if such a product should exist. At the moment the marketed so-called absorption heat pump are not actually heat pumps in winter since they just use the burner of the heat pump. An actual heat pump would deliver more useful heat than the heat delivered by the cogeneration. Let us call COA the coefficient of amplification of the hat pump: $COA = Q_{us}/Q$ where Q_{us} is the useful heat and Q is the heat delivered by the cogeneration. Then the ratio R is now given by:

$$R_{H.P.} = \frac{W \times A_{el} + \dfrac{COA \times Q}{\eta_b}}{Q_P \times A_f} = \eta_{el} \times \frac{A_{el}}{A_f} + \frac{COA}{\eta_b}\left(\eta_g - \eta_{el}\right) = \frac{\eta_g}{\eta_b} \times COA + \eta_{el}\left(\frac{A_{el}}{A_f} - \frac{COA}{\eta_b}\right) \quad [8]$$

Considering the same cases as above for $A_{el}/A_f = 3$, η_b=0.9 and COA=1.5, the ratio $R_{H.P.}$ and the CO_2 emissions saving are now (Table III and Figure III):

Table III: CO_2 emissions saving ($1-R^{-1}$) due to a heat pump

	$R_{H.P.}$	$1-R_{H.P.}^{-1}$
Case 1 S.T.	1.44	30%
Case 2 G.T.	1.56	36%
Case 3 G.E.	1.78	44%
Case 4 C.C.	2	50%

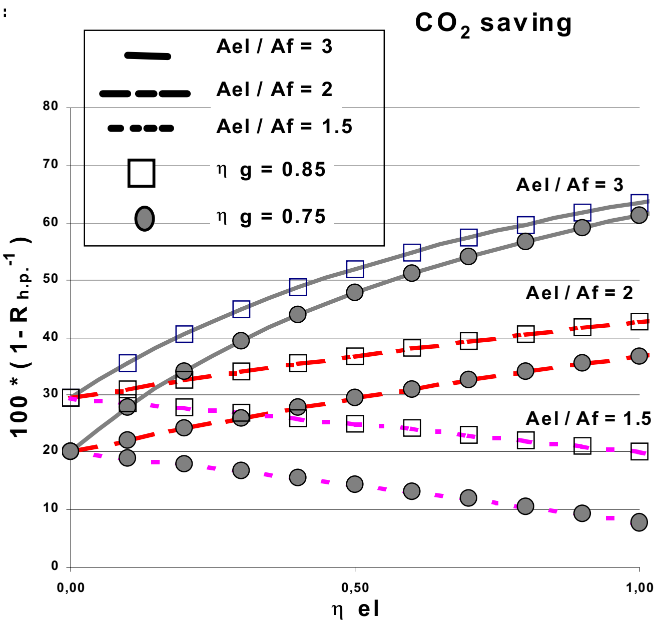

Figure 3: CO_2 saving versus η_{el} for the reversible heat pump

2.2 Total Energy System

With an adsorption heat pump, it is possible to get a high temperature lift (70°C or even more) at the cost of the COP which is less than with an absorption heat pump, however, doing so, it is possible to use at the same time the cooling and the heating effect of the heat pump. The efficiency is increased since no heat is rejected except the heat losses. Introducing the following ratios:

$$\begin{cases} \eta_g^{tot} = \dfrac{W + Q_{us} + C}{Q_P} = \\ \dfrac{W + Q \times COA + Q \times COP_{abs}}{Q_P} \\ COP_{abs} = \dfrac{C}{Q} \; and \; COA = \dfrac{Q_{us}}{Q} \end{cases}$$

One has to be careful that the ratio η_g^{tot} is not an efficiency since it can be eventually higher than 1. Without heat losses, we should get $COA=1+COP_{abs}$ but we shall assume some heat losses exist.

Following the same approach described above, the ratio R, with respect to the indirect emission due to energy consumption of the reference solution, becomes:

$$R^{tot} = \eta_{el} \times \frac{A_{el}}{A_f} + (\eta_g - \eta_{el})\left[\frac{COA}{\eta_b} + \beta \times \frac{A_{el}}{A_f}\right] \quad [9]$$

Unfortunately in that case the COP of the sorption unit will be lower than the previous COP of the double effect LiBr-water system since this system cannot operate in those conditions. We shall assume COP=0.7 and COA=1.5 which corresponds to the present state of the art of and adsorption heat pump (zeolite-water).

Considering the same cases as above for $A_{el}/A_f = 3$, $\eta_b=0.9$, COP=0.7 and COA=1.5, the ratio R_{tot} and the CO_2 emissions saving are now (Table IV and Figure IV):

Table IV: CO_2 emissions saving ($1-R^{-1}$) for a total energy system

	R_{tot}	$1-R_{tot}^{-1}$
Case 1 S.T.	1.87	46%
Case 2 G.T.	1.85	46%
Case 3 G.E.	2.03	50%
Case 4 C.C.	2.21	55%

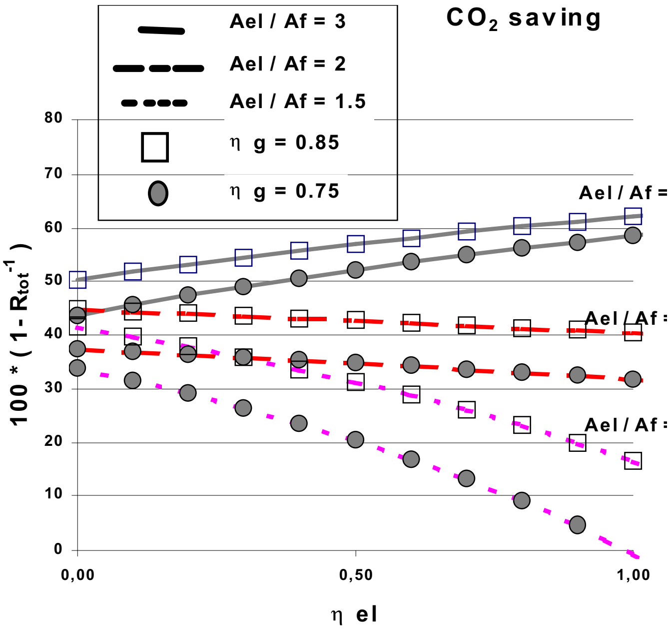

Figure 4: CO_2 saving versus η_{el} for the total energy system

3. Global impact

Consider a country where the CO_2 emissions due to electricity production are high ($A_{el}/A_f = 3$) and assume that 1/3 of the energy consumption is for heating or cooling for A.C. (1/3 for electricity and the last third being transportation and miscellaneous). Assume that half of heating and AC be provided with co- or tri-generation. Assume that the cogeneration ratios are: $\eta_b=0.9$; $\eta_g=0.8$ and $\eta_{el}=0.4$, then we get R=1.64 and the saving $(1-R^{-1})=0.4$. The cogeneration produces half of the heat but also half of the electricity in the country which corresponds to one third of the total energy consumption. As the CO_2 saving is equal to 40%, that means that the total CO_2 saving in this specific case should reach 13%. Other considerations show that the CO_2 emission saving for a large scale cogeneration use ranges from 10 to 15% depending on the conditions which is important as compared to the Kyoto protocol restrictions. Now, if the fuel used would be biofuel, the CO_2 saving would be 33%.

Even in a country like France where only 12% of the electricity comes from conventional thermal power stations, if half of this electricity, produced during peak hours, is provided by cogeneration, the CO_2 emission saving will reach 5% which is not at all negligible as compared to the Kyoto protocol restrictions.

4. Conclusions

Combined Heat, Cooling and Power units can introduce important CO_2 emissions saving provided they are judiciously used. Cogeneration and trigeneration, powered with fossil fuel, must be used only when the electricity production from the network is at high CO_2 emissions level (either in countries where the electricity production from the network is at high CO_2 emissions level or on relief of conventional thermal power stations in the other countries). The CO_2 emission saving will be all the more important if the cogeneration ratios (global and electric efficiencies) are high. The CO_2 saving can overpass 40%. The impact with respect to global environment may be important if these techniques are highly disseminated: CO_2 emission saving may reach 5% for a country like France where the electricity production from the network is at very low CO_2 emissions level but it may overpass 15% in a country where the electricity production from the network is at very high CO_2 emissions level. If biofuels are to be used, the benefit is much more important (it can reach 33%). These techniques are for sure attractive techniques to master global warming.