Business Case of a Co-Generator using an Internal Combustion Engine in Combination with a High Temperature Heat Pump.[1]

Introduction

In Italy, the price of electricity is rather high and the price of natural gas is relatively low. As a consequence, many companies have installed gas driven co-generator plants, in order to reduce their costs of energy. Most of them are using internal combustion engines (ICE's). Quite often parts of the thermal energy produced by these plants have to be dissipated in the environment because the process requesting the thermal energy, demands heat at temperatures higher than those of the cooling water and/or the intercooler. Obviously, this has dire consequences for the environmental and economic benefits of the project. Moreover, such a co-generation plant is unlikely to qualify as High Efficiency Co-generator (CAR) and is therefore not eligible for government incentives (White Certificates).

Another inconvenient of ICE co-generators is that the electricity production, typically about 40 % of the energy output, is often significantly higher than the demand for electricity on the site where it is located. In those cases, substantial amounts of electrical energy have to be transferred to the grid. The remuneration of this energy is low (about € 0,06 per kWh).

High temperature heat pumps can mitigate both problems. These heat pumps can lift the low grade heat from the cooling water and the intercooler up to temperatures around 160 [°C] and produce low pressure steam.

So, with these machines it is possible to use the electrical energy, produced by the co-generator but not needed on site, to power a heat pump in order to increase the temperature of the low-grade heat from the co-generator, to level required by the heat demanding process(es). With these new heat pumps, it is now possible to use ICE co-generators, also in cases where there is only a need for thermal energy at temperatures above 100 [°C].

This document describes a business-case of a system composed of an ICE co-generator and a high temperature heat pump. Using a simplified model, the Simple Pay-Back Time (SPBT) has been calculated. A sensitivity analysis for six system parameters is presented as well .

---

[1] Disclaimer: All the data provided in this document are for information only and do not constitute any binding commercial information or proposal. Though provided in good faith, no claim, of any kind, can be made against the author or Studio Caramelli S.r.l. on the basis of content of this document.

ICE Co-generators in Italy

In Italy there are about 1.550 high efficiency co-generators using internal combustion engines (data 2017[2]). The average electrical power installed is 1,1 [MW_e] per unit and 98,8 % of them use natural gas, GPL or LNG. The reported average thermal efficiency, in high efficiency co-generation mode, is about 31 %.

Typically these machines have an instantaneous thermal efficiency between 40 and 50 %. The difference between this two efficiencies is caused by the fact that in practice significant amounts of thermal energy produced by the co-generator, are not used.

On average one can assume that these machines transform about 46 % the primary energy into heat, delivered through the exhausts gasses, the cooling water, the intercooler and the oil cooler. So on average, approximately 15 % (46 – 31 = 15 %) of the energy input is delivered as heat, but is not used. The main reason for this waste of energy is the fact that the temperature levels of the heat produced and the process requirements, do not match. High temperature heat pumps can solve this problem by upgrading the heat to higher temperature levels, as explained previously.

In total it concerns around 2.785 [GWh] of thermal energy per year. Assuming 7.500 operating hours per year on average, the corresponding average thermal power is 375 [MW_t].

The Base Case

The schematic view of the Base-Case system used for the SPBT calculations is given in Figure 1.

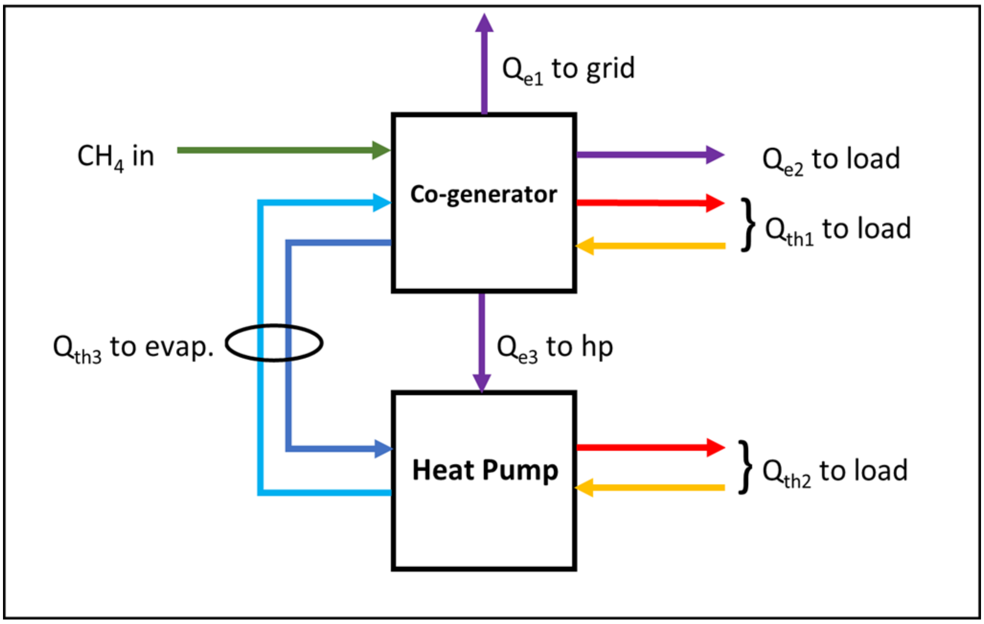

Figure 1 — Schematic view of the system.

[2] Source: "Relazione Annuale sulla Cogenerazione in Italia , Anno produzione 2017", Ministero dello Sviluppo Economico, April 2019.

It is assumed that the co-generator is operated in “thermal tracking” mode. That is, it is operated with the objective to satisfy always the total request for thermal energy. Also, for the sensitivity analysis it is assumed that the size of the co-generator and the heat pump adapt to the thermal load. The demand for electrical energy is balanced with electrical energy taken from, or fed into, the grid.

The simplified model used for the calculation of the annual amounts of energy, is composed of the five equations below (see Figure 1 and Table 1 for the definition of the parameters):

$$\text{Thermal load} = Qth_1 + Qth_2 \quad (1)$$

$$Qth_1 = \eta_{ht} \times CH_4 \quad (2)$$

$$Qth_3 = \eta_{lt} \times CH_4 \quad (3)$$

$$Qe_1 + Qe_2 + Qe_3 = \eta_e \times CH_4 \quad (4)$$

$$Qth_2 = Qth_3/(1-(1/COP)) \quad (5)$$

The values of the parameters used for the Base-Case scenario are listed in Table 1, here below. The data refer to one year of operation.

Table 1 — Input data used for the Base-Case scenario.

Load data:	Value:	M.U.
Electrical load (Q_{e2})	5.000	MWh
Thermal load ($Q_{th1} + Q_{th2}$)	10.000	MWh
Hours of operation	6.000	hrs
Electrical efficiency CHP (η_e)	37%	-
Thermal efficiency CHP high temperatures > 100 °C (η_{ht})	24,6%	-
Thermal efficiency CHP low temperatures < 100 °C (η_{lt})	24,5%	-
Overall efficiency CHP	86,1%	
COP Heat pump	4	-
Cost data:		
Costs CH_4	0,29	€/smc
Costs electricity from grid	0,11	€/kWh$_e$
Reimbursement for electricity fed into the grid	0,06	€/kWh$_e$
Specific investment costs co-generator	0,8	k€/kW$_e$
Specific investment costs heat pump	0,45	k€/kW$_{th}$
O & M Heatpump	1	€/hr
O & M Cogenerator	11	€/hr

Energy performance

The calculated yearly energy flows are given in Table 2. It is assumed that the request for thermal energy and electrical energy are perfectly matched in time. So all the electrical energy and all the thermal energy are generated in co-generation mode.

From Table 2, it results that the system is well balanced in the sense that only 0,5 % of the electrical energy produced, is fed into the grid.

Table 2 — Calculated energy flows for one year of operation.

Flow	Amount	Unit
Qth_1	4.296	MWh_t
Qth_2	5.704	MWh_t
Qth_3	4.278	MWh_t
CH_4	17.462	MWh
CH_4	1.818.976	smc
$Qe_1+Qe_2+Qe_3$	6.461	MWh_e
Qe_1	35	MWh_e
Qe_2	5000	MWh_e
Qe_3	1.426	MWh_e
$Pcogen_{electr.}$	1,077	MW_e
$Php_{therm.}$	0,951	MW_t

Where: $Pcogen_{electr.}$ = Installed electrical power of the co-generator.

and: $Php_{therm.}$ = Installed thermal power of the heat pump.

Economic performance

Using the cost data from Table 1 and the energy flows from Table 2, the investment costs and the yearly operation costs and benefits, have been calculated. The results are listed in Table 3.

From Table 3, it can been seen that the simple pay-back time (SPBT) of the combined system with the input parameters as listed in Table 1, is about 3,5 years.

It should be noted that no incentives are included in this assessment of the economic performance.

Table 3 — Economic performance and SPBT.

Investment costs:		
Co-generator	861	k€
Heat pump	428	k€
Total:	1.289	k€
Annual running costs:		
CH_4 for co-generator	528	k€
O & M	72	k€
Total:	600	k€
Avoided costs for energy:		
Value thermal energy*	336	k€
Value electrical energy	638	k€
Total:	973	k€
Yearly savings:	374	k€
SPBT:	3,45	yrs

* Boiler efficiency = 0,90

Sensitivity analysis

In order to better understand how the different parameters impact the system performance, a sensitivity analysis has been carried out. The SPBT has been calculated for different values of six principle parameters, when they vary between + 40 % and – 40 % of their Base-Case value.

The results are shown in Figure 2. From this figure it can be seen that for five of the six parameters a variation of +/- 40 % around the base-case values, does not modify the SPBT by more than 1,3 [yrs].

The parameter which has most impact on the system economics, is the number of annual operating hours. When the system is operated for 8.400 [hrs] per year, instead of the 6000 [hrs] assumed for the Base-Case, the SPBT is reduced to about 2,7 [yrs].

The impact of the COP is rather limited. A higher COP does not automatically bring a better SPBT. This is due to the fact that when the COP increases the co-generator has to produce more heat in order to match the same thermal load. This results in a higher Capex (larger co-generator) and more electricity fed into the grid (lower benefits).

So, when the heat demanding process requires relatively high temperatures, for example higher than 140 [°C], the lower COP will not have major consequences for the SPBT. For example, a COP of 2,4 instead of 4,0 will add only 0,74 [yrs] to the SPBT.

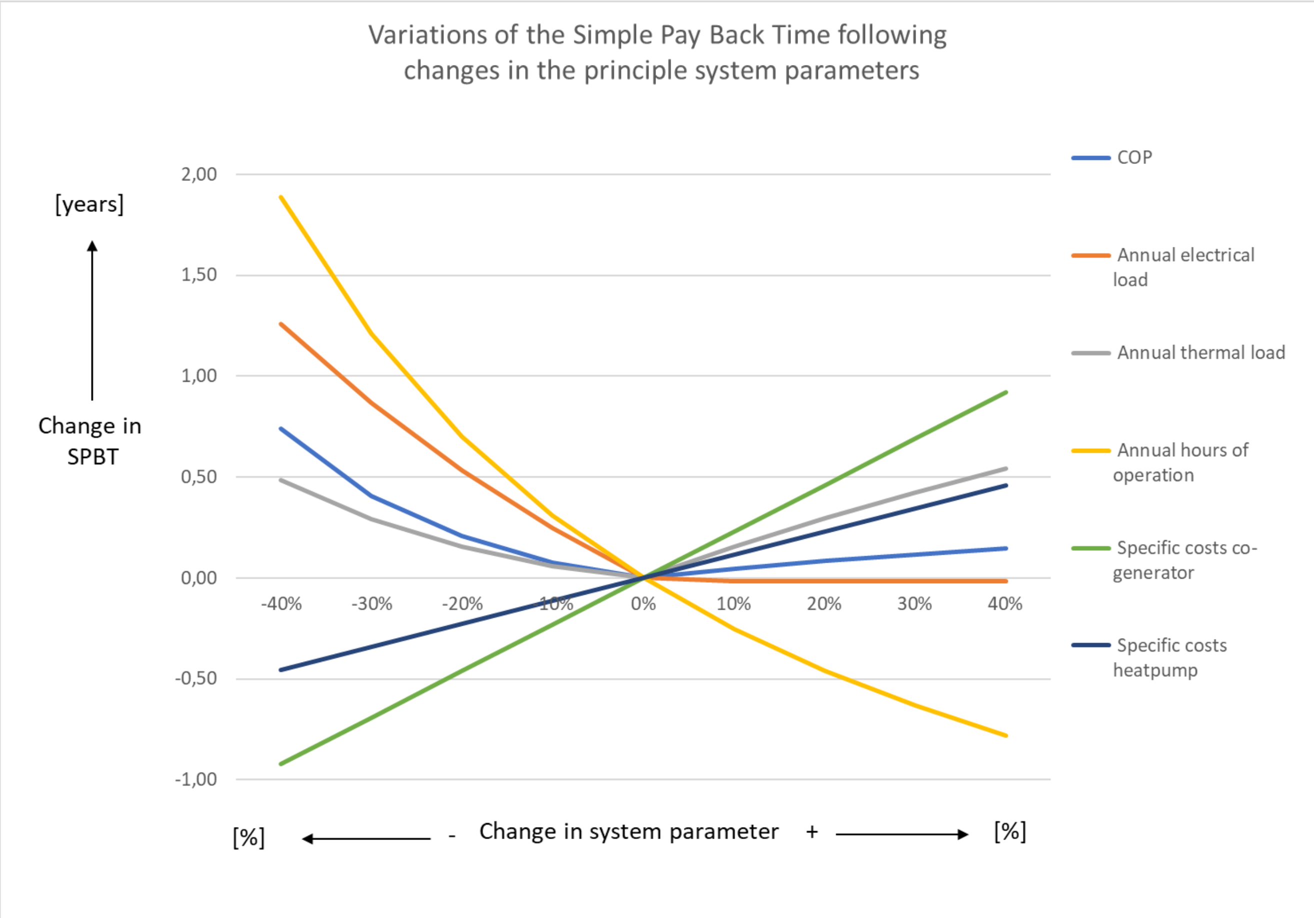

Fig. 2 — Results of the sensitivity analysis.

Verification High Efficiency Co-generator (CAR)

In order to be recognised as High Efficiency Co-generator (CAR) the following conditions must be fulfilled: $\eta_{global} > 75\ \%$ (when ICE) (6)

If $P_{electric} >$ 1MW$_e$ then PES[3] must be > 10 % (7)

If $P_{electric} <$ 1MW$_e$ then PES must be > 0 % (8)

Since almost all the electrical energy, used by the compressor, is returned as heat, the global efficiency of the combined solution is the same as the global efficiency of the co-generator when all the thermal heat is used directly by the process. This is the case, because the definition of the global efficiency for co-generators attributes the same weight to the thermal energy as to the electrical energy.

For the combined system the η_{global} is:

[3] PES = Primary Energy Savings

$$\eta_{global} = (Qe_1 + Qe_2 + Qth_1 + Qth_2)/CH_4 = 86{,}1\ \%\ .$$

It should be noted that this efficiency is independent of the COP of the heat pump.

When the global efficiency is calculated for the case no heat pump is present and only the thermal energy produced above 100 [°C] is used, the global efficiency becomes:

$$\eta_{global} = (Qe_1 + Qe_2 + Qe_3 + Qth_1)/CH_4 = 61{,}1\ \%$$

So the heat pump can improve significantly the global efficiency of the co-generator and help to pass the limit for the recognition as High Efficiency Co-generator (CAR).

The heat pump has also an impact on the primary energy savings (PES). The PES for the Base-Case system are equal to 15,6 % (with the reference efficiencies defined as: ηrif_{th} = 0,90 and ηrif_{e} = 0,525). When the same calculation is made for the case that only the heat available at temperatures above 100 [°C] is used, the PES would be – 2,2 % (negative primary energy savings).

So, adding a heat pump to a co-generator can help to satisfy the conditions for the qualification as a High Efficiency Co-generator (CAR).

Conclusions

Combining an ICE co-generator with a high temperature heat pump can bring important economic and environmental benefits in those cases in which the heat demanding process needs most of the thermal energy at levels well above 100 [°C].

The sensitivity analysis suggests that the best SPBT's are obtained when the number of hours of operation is high and the amount of electrical energy fed into the grid is low. The COP of the heat pump does not have a very strong effect on the simple pay-back time.

The data on the amount of thermal energy produced by existing ICE co-generation systems in Italy, indicate that there is a significant market potential for adding high temperature heat pumps to these installations. It is estimated that with this technique a flow of about 375 [MW] of thermal energy can be recuperated at a cost of circa 94 [MW] of electrical power.

Adding a high temperature heat pump to an ICE co-generator will improve the global efficiency and the primary energy savings of the plant. In this manner a combined plant could satisfy the conditions necessary for the qualification as a High Efficiency Co-generator (CAR) and become eligible for incentives.

Sesto Calende, 03/06/2021

Dolf van Hattem

Mail: dolf.vanhattem@studiocaramelli.com