Optimization of a distributed trigeneration system with heating micro-grids for an industrial area

Mauro Reini[1], Dario Buoro[2], Claudio Covassin[1], Alberto De Nardi[1], Piero Pinamonti[2]

[1] Department of Mechanical and Naval Engineering, University of Trieste, via Valerio 8, 34127 Trieste, Italy
[2] Energy and Turbomachinery Department, University of Udine, via delle Scienze 208, 33100 Udine, Italy

Abstract

In the paper an optimization study of a distributed trigeneration system for an industrial area is presented. The energy users located in the area are connected by existent district heating (DH) micro-grids, than the required heat can be produced by small scale CHP systems (e.g. micro gas turbines or internal combustion engine) or by a bigger and centralized CHP plant. Conventional integration boilers also can be installed inside the factories or in a centralized plant. The trigeneration system includes a set of absorption chillers, powered by cogenerated heat, used to produce cooling energy in substitution of conventional vapour compression chillers. The optimisation has to determine the optimal structure of the system, the size and the load of each component inside the optimal solution, taking into account also the thermal inertia of the DH network. The optimization is based on a Mixed Integer Linear Programming (MILP) model and it takes into account as objective function the total annual cost for purchasing, maintaining and operating the whole trigeneration system. The model allows to generate different optimal solutions by varying the boundary economic conditions (amortization period of the equipment, its capital cost, etc.), simulating different possible scenarios and estimating the possible energetic and economic savings.

Keywords

Optimization, Trigeneration system, District heating, Mixed Integer Linear Programming.

1 Introduction

Distributed cogeneration (CHP) and trigeneration (CHCP) systems allow achieving economic and energetic savings, both in residential and industrial sectors. Especially considering a set of industrial users, characterized by quite constant and high energy consumptions all year long, the adoption of such a solution can lead to increase the whole energy efficiency of the system (utilizing heat that otherwise would be wasted) and thus to reduce cost, primary energy utilization and polluting emissions. However, the expected performances could not be obtained without adopting the configuration and the operation strategy resulting from an optimization procedure of the whole system [1-5].

The study presents the optimization of a distributed CHCP system, designed to supply thermal, cooling and electrical energy to six facilities located in an industrial area in the north east of Italy. The layout and size of the network is predefined and the demands for electrical energy, cold water and steam are known in advance as well. All users are connected each other through a district heating micro-grid, therefore the related production units could send heat to the DH (district heating) network, while only the production units related to users requiring cooling power could be equipped with absorption chillers, driven by cogenerated heat. Heat and electric power could be provided either by a big centralized CHP plant (internal combustion engine

Corresponding author: Mauro Reini, reini@units.it

ICE) or by small-scale CHP systems (ICE or micro gas turbines MTG), properly located close to, or inside, the factories. Conventional integration boilers and vapour compression chillers can also be installed inside the factories or in the centralized plant, and moreover each unit is connected to the electricity network. Thus, a centralization-decentralization problem arises: if the heat would be produce and exploit locally, investments may avoid in pipelines, but, on the other hand, a single centralized energy conversion plant may entail (thank to scale economies) a smaller investment than many small decentralized conversion units of comparable total capacity [6]. The optimal solution is a compromise that depends on many variables; it is so very difficult to find the best solution without solving an optimization problem.

A problem under similar conditions was handled by Sakawa et al. [7] and other literature is available [8-11] dealing with the optimal design of district heating systems. However, these models generally consider residential users, rather than industrial ones. In [12] an example of optimisation models for industrial district heating networks is developed.

In previous works of the authors Mixed Integer Linear Program (MILP) models have been developed to optimize the design and operation of CHCP distributed generation systems in a tertiary sector scenario, considering different technologies and taking into account the effects of various economic support policies [13-16]. In this study, the thermal inertia of the district heating network is also evaluated now, applying the model to an industrial scenario. The defined equations are similar to those used for describing the presence of a thermal storage [17-21], with the difference that thermal inertia can not be regarded as an option, in the optimal strategy definition, while the usage of the storage can be.

The dynamic of the DH network could affect the operation of the whole heating system. This is due to the time delays in the transportation of the heat from the production plant to the consumers, to the heat temporary stored in the pipes and to the heat losses. The transportation time varies for the individual user according to the distance from the production plant and to the flow velocity in the pipes. To find the best operation of the system, it is therefore necessary to have an appropriate simulation model of the available district heating [22].

The model used to solve the optimization problem is based on a Mixed Integer Linear Program (MILP) and its aim is to determine which is the best configuration and operation in terms of both economical and environmental benefits. The objective function takes into account the total annual cost for purchasing, maintaining and operating the whole trigeneration system. The optimization is subjected to the constraints that express components operation, the energy balances of nodes, and to the economic boundary conditions (e.g. incomes from the sale of electricity, prices of fuel and electricity, etc.). The optimization specifies the size, the kind and the location of cogeneration equipments, absorption machines, integration boilers and compression chillers present in the superstructure, as well as the optimal operation of each component inside the optimal solution. The conventional solution can otherwise be adopted: all the electricity would be bought from the grid, the thermal energy would be produced by boilers and the cooling energy by compression chillers, driven by electricity bought from the grid.

2 The case study

The six users considered in the study belong to different economic sectors, like food, furniture, engineering and tertiary. Despite their production type is not homogeneous each of them is characterized by quite regular energy demands along the year, that can be known in advance.

As user 1 requires all the three kind of energy vectors (electrical, thermal and cooling power), its case is considered as a valid example to represent the energetic consumptions of a typical food company. It needs cooling energy at a very low temperature in order to keep the food refrigerated (-25°C). figure 1, figure 2 and figure 3 represent its annual electrical, thermal and cooling consumption respectively, while the figure 4 shows the three cumulative energetic curves.

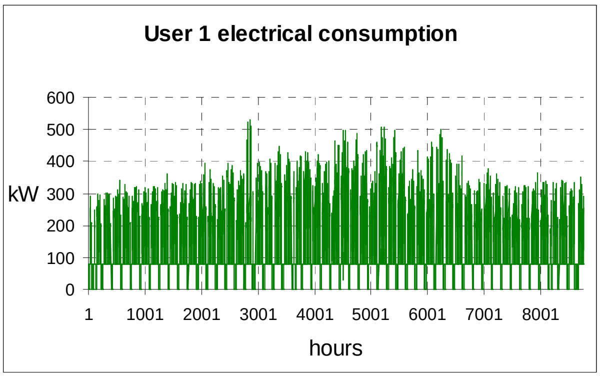

Figure 1: User 1 electrical consumption

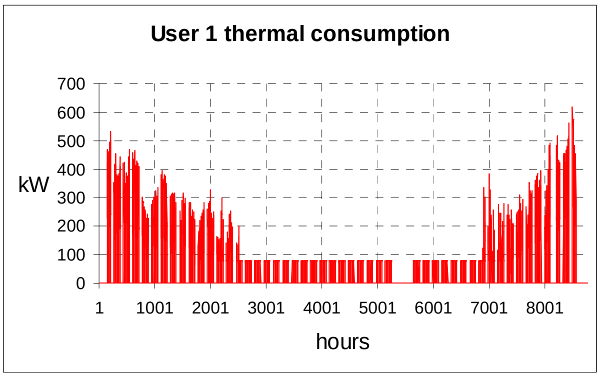

Figure 2: User 1 thermal consumption

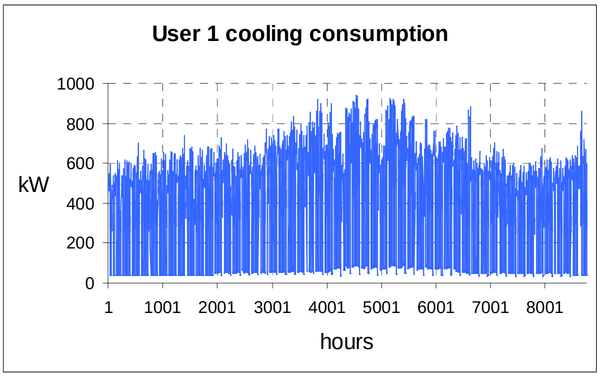

Figure 3: User 1 cooling consumption

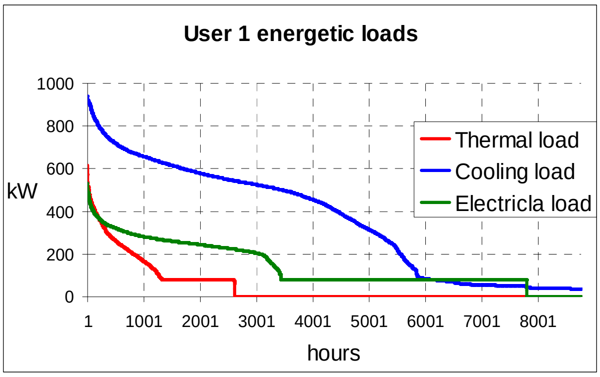

Figure 4: User 1 energetic loads

It can be noted from figure 2 that the thermal load is higher during coldest months, when heating is operating, while during the remaining months only process heat is required. Figure 3 shows that cooling demand is higher than zero all year long (food must always be kept cooled) and that the consumption is highest during hottest months (summer time). It is possible to see (figure 4) that electrical demand is constant for at least 4,000 hours a year. This is due to the constant load during night.

Taking into account all the six users aggregated demands, their electrical, thermal and cooling consumption profiles and the cumulative energetic curves are shown below (figure 5, figure 6, figure 7 and figure 8). Looking at the thermal trend of figure 6 it can be noted that process heat is needed during central months too. Figure 7 represents the sum of the annual cooling consumptions of users 1 and 2, as the other users have not cooling demand. The electric load curve of figure 8 does not include the electricity needed to power the chillers.

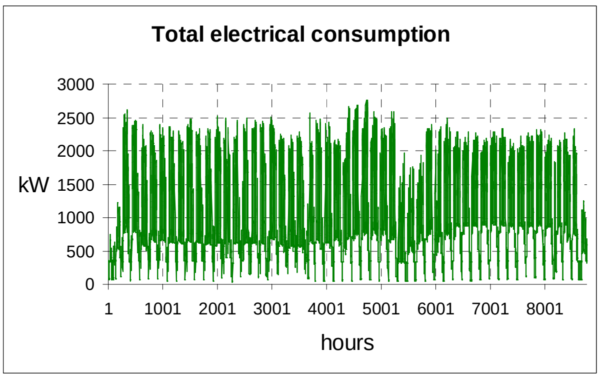

Figure 5: Total electrical consumption

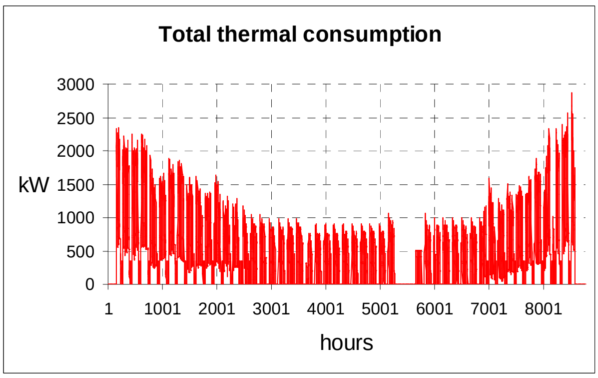

Figure 6: Total thermal consumption

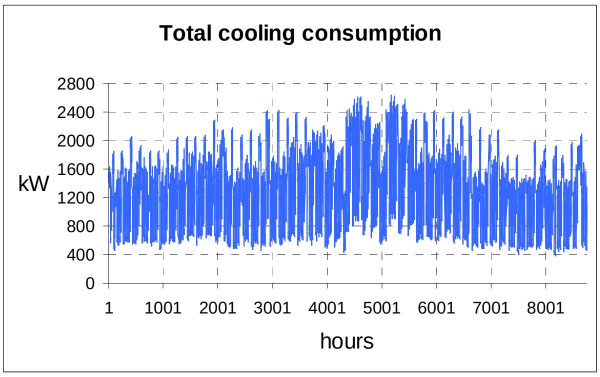

Figure 7: Total cooling consumption

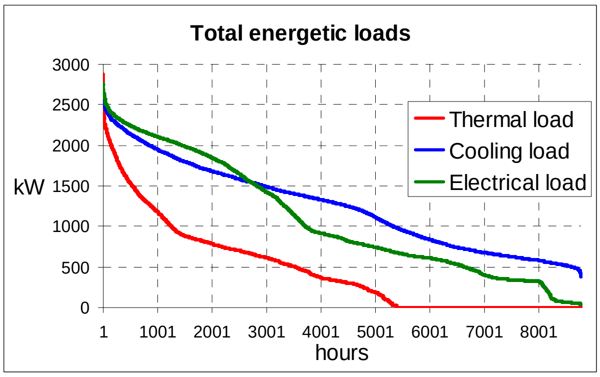

Figure 8: Total energetic loads

Table 1: User energetic demands

	ELECTRIC		HEATING		COOLING	
	Peak power [kW_{el}]	Year dem. [MWh_e]	Peak power [kW_{th}]	Year dem. [MWh_{th}]	Peak power [kW_c]	Year dem. [MWh_c]
User 1	449	1.241	518	393	836	3.140
User 2	878	1.824	-	-	1.697	7.783
User 3	801	1.607	686	1.008	-	-
User 4	652	1.710	996	1.700	-	-
User 5	742	3.049	516	790	-	-
User 6	14	62	136	115	-	-
Total	2.768	9.483	2.850	4.006	2.533	10.923

Table 1 shows the pick power and the yearly energetic demand for each user. Total pick power is the maximum hourly energy demand of the all six users, and it is lower than the sum of the single user picks. In order to reduce the variables number and the model complexity, it has been decided to represent the whole year by twelve typical weeks (1 week per month), each composed by seven days of 24 hours. This kind of discretisation allows keeping a realistic picture of the actual annual behaviour and also allows the thermal inertia of the network producing its effect on the optimal operation.

Table 2: Component size and size limits

	COGENERATOR TYPES AND SIZES			BOILER SIZES		ABS./COMP. CHILLER SIZES
	Type	Min kW	Max kW	Min kW	Max kW	kW
Central Unit	ICE	300	2.600	150	2.500	-
Unit 1	TG	500	500	150	2.000	900
Unit 2	ICE	300	2.400	-	-	1.700
Unit 3	MTG	300	300	150	2.000	-
Unit 4	MTG	300	300	150	2.000	-
Unit 5	MTG	100	100	150	2.000	-
Unit 6	MTG	30	30	150	2.000	-

A preliminary analysis of the user requirements, shown in Table 1, have led to Table 2, that shows the minimum and maximum sizes considered in the optimization procedure for the machines that could be installed. The table shows the same value for minimum and maximum when the size is fixed in advance.
The evaluation of the system operative cost generally needs the hourly costs of the energetic vectors to be defined (gas and electric energy) as both input and output. The model is applied to

users located in the north-east of Italy and the price of bought and sold electric energy has been assumed constant (in previous works [13-16] the hourly variation of price did not affect the optimal solution, if a mean value had been assumed). This choice is consistent with the real situation where the energy market determines the energy prices, without being affected by individual market operators. Moreover, according to Italian legislation, different values of gas price have been assumed for supplying micro-gas turbines and boilers, because of the different taxation level between cogeneration gas and gas for heating purpose, in the tertiary sector. Table 3 shows the energy prices used in the application. Component prices have been considered constant, or linear vs. their size [6], in both cases cost coefficients are shown in Table 4. In the study, 20 years have been considered as life span for absorption machines, 15 years for cogenerators and boilers and 10 years for compression chillers.

Table 3: Energy prices [€/kWh]

Electricity purchased	Electricity sold	CHP gas	Boiler gas
0,15	0,12	0,045	0,059

Table 4: Component cost

Unit	COGENERATOR		BOILER		ABS. CH.	COMP. CH.
	Fix. cost [€]	Var. Cost [€/kW$_{el}$]	Fix. cost [€]	Var. Cost [€/kW$_{el}$]	Fix. cost [€]	Fix. cost [€]
Central	130.000	730	6.300	17,8	-	-
1	130.000	730	6.300	17,8	260.000	125.000
2	130.000	730	6.300	17,8	400.000	240.000
3	160.000		6.300	17,8	-	-
4	160.000		6.300	17,8	-	-
5	140.000		6.300	17,8	-	-
6	70.000		6.300	17,8	-	-

3 The superstructure

As mentioned in the introduction, the six facilities involved in the study are supposed to be connected by an already existing heating network, and their energy demands are known in advance. They all can transfer heat to and from the network, if some constraints are respected, as well as exchange electricity with the electric grid.

Figure 9 shows the superstructure, where all possible considered options are included. As it can be seen, in the centralized unit (unit 0) a CHP system and a boiler can be adopted. Unit 1 can incorporate a CHP system directly connected with an absorption chiller, which cannot be driven by heat from the network due to the different temperature levels, a boiler and a compression chiller. User 2 does not require heating energy, so that a boiler has not been included in the superstructure. In this unit a compression chiller and an absorption chiller, which can be powered either by cogenerated heat or by heat from the network, are enclosed. The remaining production units have the same superstructure and they include only a CHP system and a boiler because they do not require cooling energy. In those units the superstructure is equivalent, but the components can have different sizes, as it can be seen in Table 2.

4 The MILP model

Recently a lot of research works have been carried out to optimize the design and operation of distributed cogeneration and trigeneration energy systems [23-25] integrated also with the district heating network [1, 5, 6, 21]. In a distributed generation context, the optimal solution depends on the trade-off between the scale economies, which can play an important role in centralization option, and the additional costs of equipment replication, connected to decentralized solutions. A MILP model has been used for properly describing by means of binary variables the choice of centralized/decentralized components inside the superstructure, as well as the on/off operation of chosen components, in the optimal operation strategy.

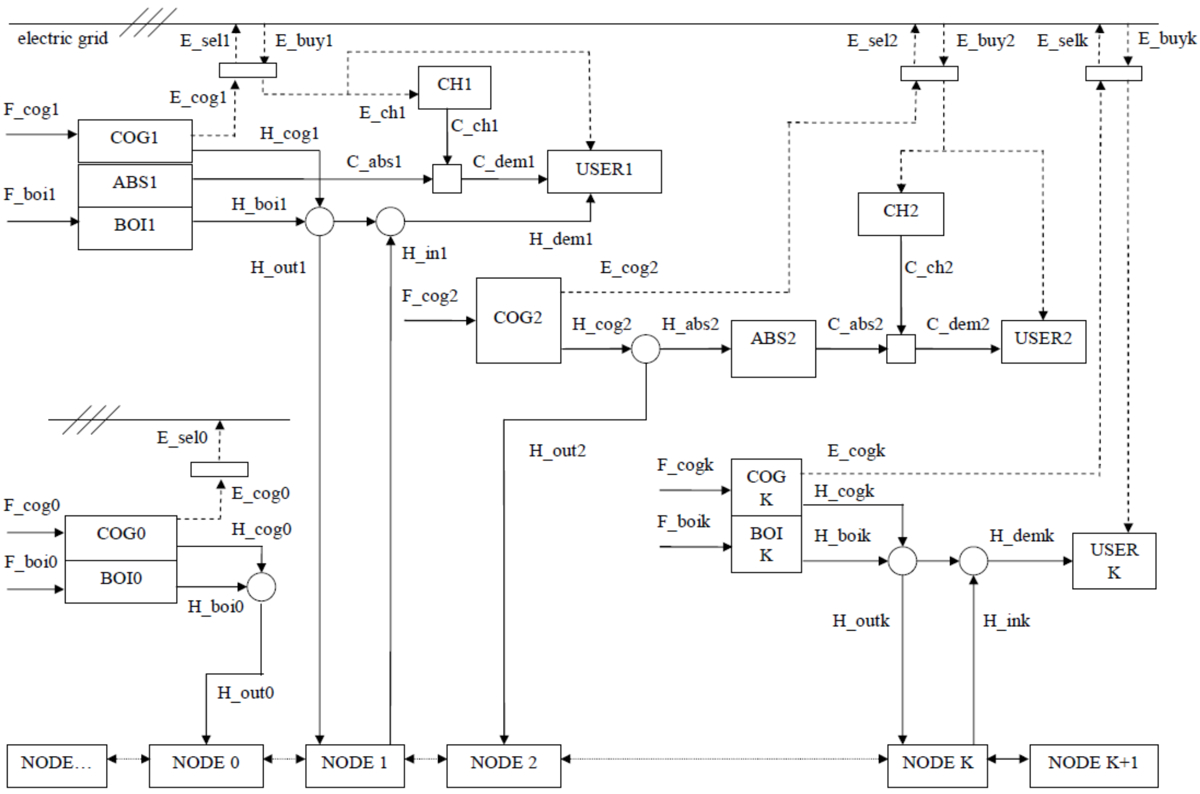

Figure 9: The superstructure

The mathematical problem of optimizing the operation of a CHCP plant has to be generally regarded as a variational calculus problem, because the optimization variables expressing partial load operation of each component are time dependent. However, a realistic description of the system may be represented by a MILP formulation by properly discretizing the load curves and approximating performance maps with a set of linear functions. In this work, the problem is regarded as a quasi-stationary one and a set of discrete time intervals of one hour describe the whole year.

Previous works [13-16] have examined the optimization of both production units and district heating networks, without taking into account their thermal inertia. In this paper, the network is assumed as already present, while the production units are optimized considering also the thermal inertia of the pipes. This allows understanding if it plays an important role in the unit optimization or if it could be neglected without significantly affecting the optimal solution.

In the proposed model, different type of production units have been introduced assuming different kinds of internal superstructures (see Figure 9); it could be easily generalized to various industrial areas, or to other kind of energy user network.

Model Constraints

In the MILP optimization procedure, three main different types of constraints can be identified:

- Components constraints: relate output and input energy of each component;
- Energy balances: ensure that the amount of input energy is equal to the output, for each time interval and for each node;
- Network constraints: relate thermal losses, thermal contributions from the units and thermal energy delivered to the users, taking into account also the thermal inertia.

Component constraints

In this paper the components (cogenerators, boilers, absorption machine and compression chillers) are of two kinds: components where the size is fixed and components where it is not. For the first set of components, a binary decision variable is introduced to express the existence,

a binary and a continuous variable, for each time interval, are introduced to express respectively the on/off status of the component and the load level.
In the following equations, the decision variables are typed in **bold**, index *h* represent time interval, and index *u* the energy unit associated to a user, inside the superstructure. The other coefficient typed in *italic*, derived from a linear regression of the machine performance curves.
The cogenerators with fixed size can be modelled as:

$$\mathrm{Hcog}_{h,u} = p_{h,u} \cdot \mathbf{Ecog}_{h,u} + q_{h,u} \cdot \mathbf{opcog}_{h,u} \tag{1}$$

$$\mathrm{Fcog}_{h,u} = r_{h,u} \cdot \mathbf{Ecog}_{h,u} + s_{h,u} \cdot \mathbf{opcog}_{h,u} \tag{2}$$

$$\underline{\mathrm{Ecog}}_{u} \cdot \mathbf{opcog}_{h,u} \le \mathbf{Ecog}_{h,u} \le \overline{\mathrm{Ecog}}_{u} \cdot \mathbf{opcog}_{h,u} \tag{3}$$

$$\mathbf{opcog}_{h,u} \le \mathbf{excog}_{h,u} \tag{4}$$

The absorption machines can be modelled as:

$$\mathrm{Habs}_{h,u} = a_{h,u} \cdot \mathbf{Cabs}_{h,u} + b_{h,u} \cdot \mathbf{opabs}_{h,u} \tag{5}$$

$$\underline{\mathrm{Cabs}}_{u} \cdot \mathbf{op\_abs}_{h,u} \le \mathbf{Cabs}_{h,u} \le \overline{\mathrm{Cabs}}_{u} \cdot \mathbf{opabs}_{h,u} \tag{6}$$

$$\mathbf{opabs}_{h,u} \le \mathbf{exabs}_{h,u} \tag{7}$$

The compression chillers can be modelled as:

$$\mathrm{Ech}_{h,u} = c_{h,u} \cdot \mathbf{Cch}_{h,u} + d_{h,u} \cdot \mathbf{opch}_{h,u} \tag{8}$$

$$\underline{\mathrm{Cch}}_{u} \cdot \mathbf{opch}_{h,u} \le \mathbf{Cch}_{h,u} \le \overline{\mathrm{Cch}}_{u} \cdot \mathbf{opch}_{h,u} \tag{9}$$

$$\mathbf{opch}_{h,u} \le \mathbf{exch}_{h,u} \tag{10}$$

Equations 1, 2, 5 and 8 relate the main energy product of the component with its input consumption and subproduct, equations 3, 6 and 9 determine the lower and upper load limits while the equations 4, 7 and 10 state that the relate component can be turned on only if it is present in the superstructure.
If the size is not known in advance, a binary variable represents the existence of the component; a continuous variable represents the size, whereas a binary and a continuous variable, for each time interval, represent the on/off status and the load level respectively. Another auxiliary continuous variable has to be introduced to make the model linear, for each time interval.
The cogenerators can be modelled as:

$$\mathrm{Hcog}_{h,u} = e_{h,u} \cdot \mathbf{Ecog}_{h,u} + f_{h,u} \cdot \mathrm{o}\mathbf{pcog}_{h,u} + g_{h,u} \cdot \boldsymbol{\delta}_{h,u} \tag{11}$$

$$\mathrm{Fcog}_{h,u} = l_{h,u} \cdot \mathbf{Ecog}_{h,u} + m_{h,u} \cdot \mathbf{opcog}_{h,u} + n_{h,u} \cdot \boldsymbol{\delta}_{h,u} \tag{12}$$

$$\underline{\mathrm{Ecog}}^{I}_{u} \cdot \mathbf{opcog}_{h,u} + \underline{\mathrm{Ecog}}^{II}_{u} \cdot \boldsymbol{\delta}_{u} \le \mathbf{Ecog}_{h,u} \le \overline{\mathrm{Ecog}}^{I}_{u} \cdot \mathbf{opcog}_{h,u} + \overline{\mathrm{Ecog}}^{II}_{u} \cdot \boldsymbol{\delta}_{u} \tag{13}$$

$$\mathbf{scog}_{u} + \overline{\mathrm{scog}}_{u} \cdot \left(\mathbf{opcog}_{h,u} - 1\right) \le \boldsymbol{\delta}_{h,u} \le \mathbf{scog}_{u} \tag{14}$$

$$\underline{\mathrm{scog}}_{u} \cdot \mathbf{opcog}_{h,u} \le \boldsymbol{\delta}_{h,u} \le \overline{\mathrm{scog}}_{u} \cdot \mathbf{opcog}_{h,u} \tag{15}$$

$$\underline{\mathrm{scog}}_{u} \cdot \mathbf{excog}_{u} \le \mathbf{scog}_{h,u} \le \overline{\mathrm{scog}}_{u} \cdot \mathbf{excog}_{h,u} \tag{16}$$

$$\mathbf{opcog}_{h,u} \le \mathbf{excog}_{h,u} \tag{17}$$

The boiler can be modelled as:

$$\mathrm{Fboi}_{h,u} = j_{h,u} \cdot \mathbf{Hboi}_{h,u} + k_{h,u} \cdot \mathbf{opboi}_{h,u} + w_{h,u} \cdot \boldsymbol{\gamma}_{h,u} \tag{18}$$

$$\underline{\mathrm{Hboi}}^{I}_{u} \cdot \mathbf{opboi}_{h,u} + \underline{\mathrm{Hboi}}^{II}_{u} \cdot \boldsymbol{\gamma}_{u} \le \mathbf{Hboi}_{h,u} \le \overline{\mathrm{Hboi}}^{I}_{u} \cdot \mathbf{opboi}_{h,u} + \overline{\mathrm{Hboi}}^{II}_{u} \cdot \boldsymbol{\gamma}_{u} \tag{19}$$

$$\mathbf{sboi}_{u} + \overline{\mathrm{sboi}}_{u} \cdot \left(\mathbf{opboi}_{h,u} - 1\right) \le \boldsymbol{\gamma}_{h,u} \le \mathbf{sboi}_{u} \tag{20}$$

$$\underline{\mathrm{sboi}}_{u} \cdot \mathbf{opboi}_{h,u} \le \boldsymbol{\gamma}_{h,u} \le \overline{\mathrm{sboi}}_{u} \cdot \mathbf{opboi}_{h,u} \tag{21}$$

$$\underline{\mathrm{sboi}}_{u} \cdot \mathbf{exboi}_{u} \le \mathbf{sboi}_{h,u} \le \overline{\mathrm{sboi}}_{u} \cdot \mathbf{exboi}_{h,u} \tag{22}$$

$$\mathbf{opboi}_{h,u} \le \mathbf{exboi}_{h,u} \tag{23}$$

Taking into account that the size is a decision variable, some more constraints have to be introduced with respect to the modelisation presented before. Equations 15, 16, 21 and 22 are needed to express the size variation options, keeping the model linear; they also express the lower and upper limits for the size of each component.

Energy balance constraints

$$\mathbf{Ecog}_{h,u} + \mathbf{Ebuy}_{h,u} - \mathrm{Edem}_{h,u} - \mathrm{Ech}_{h,u} - \mathrm{Esel}_{h,u} = 0 \quad (24)$$

$$\mathrm{Hcog}_{h,u} + \mathbf{Hboi}_{h,u} + \mathbf{Hin}_{h,u} - \mathrm{Habs}_{h,u} - \mathbf{Hwas}_{h,u} - \mathrm{Hdem}_{h,u} = 0 \quad (25)$$

$$\mathbf{Cabs}_{h,u} + \mathbf{Cch}_{h,u} - \mathrm{Cdem}_{h,u} - \mathbf{Cwas}_{h,u} = 0 \quad (26)$$

In equation 25 *Hin* expresses heat sent to other users through the network. It is negative when the user receives energy from the heating network.

Network constraints

Following constrains represents the network behavior, taking into account the energy stored (eq. 27), the energy losses through pipelines (eq. 28), the energy balance (eq. 29) and other constraints (eq. 30, 31) assuring that heat can be sent to the user only if the temperature of the water inside the network is greater than a minimum level depending on the user type.

$$\mathrm{Qgrid}_h = \frac{\pi \cdot d^2}{4} \cdot l \cdot \rho \cdot cp \cdot (\mathbf{t}_h - \mathbf{t}_{h-1}) \quad (27)$$

$$\mathrm{Qwas}_h = k \cdot (\mathbf{t}_t - \mathrm{tground}) \quad (28)$$

$$\sum_u \mathbf{Hin}_{h,u} - \mathrm{Qgrid}_h - \mathrm{Qwas}_h = 0 \quad (29)$$

$$\mathbf{Hin}_{h,u} \le \mathrm{H\,max} \cdot \boldsymbol{\lambda}_{h,u} \quad (30)$$

$$\mathbf{t}_h \le \mathrm{t\,min}_u \cdot \boldsymbol{\lambda}_{h,u} \quad (31)$$

<u>Objective Function</u>

The Objective Function represents the total annual cost (eq.35) and includes investment costs of components (eq.32), purchasing electricity cost, income from the sale of electricity, cost of fuel used in cogenerators and boilers (eq. 33), and machine maintenance costs (eq. 34).

$$inv\cos t = \sum_u Ccog_u^I \cdot \mathrm{excog}_u + Ccog_u^{II} \cdot \mathrm{scog}_u + Cboi_u^I \cdot \mathrm{exboi}_u + Cboi_u^{II} \cdot \mathrm{sboi}_u + \\ + Coabs_u \cdot \mathrm{exabs}_u + Coch_u \cdot \mathrm{exch}_u \quad (32)$$

$$\mathrm{opcost} = \sum_{h,u} \left(\mathrm{Cbuy} \cdot \mathbf{Ebuy}_{h,u} + \mathrm{Cgcog} \cdot \mathrm{Fcog}_{h,u} + \mathrm{Cgboi} \cdot \mathrm{Fboi}_{h,u} - \mathrm{Csel} \cdot \mathrm{Esel}_{h,u} \right) \quad (33)$$

$$\mathrm{mcost} = \sum_{h,u} \left(\mathrm{Mcog} \cdot \mathbf{Ecog}_{h,u} + \mathrm{Mboi} \cdot \mathbf{Hboi}_{h,u} + \mathrm{Mabs} \cdot \mathbf{Cabs}_{h,u} + \mathrm{Mch} \cdot \mathbf{Cch}_{h,u} \right) \quad (34)$$

$$\mathrm{Fobj} = \mathrm{opcost} + \mathrm{mcost} + \mathrm{invcost} \quad (35)$$

This objective function is linear with respect to independent variables described before and it has to be optimized subjected to constraints expressed in equations 1-31. The existence and the on/off status of each component have been described in the model by means of binary variables. The existence variables are generally decision variables during the optimization process, but can also be set by the analyst to enable or to force the choice of some components. For example, when determining the optimal solution of conventional energy supply system, consisting of boilers and refrigerators, the integer variables corresponding to cogenerators and absorption machines are set to zero.

5 Results

The optimization problem has been solved in five different scenarios; the results, presented in table 5, are compared with the case of conventional energy supply. The six situations are:

- Case 0, conventional energy supply;

- Case 1, global optimal solution;
- Case 2, optimal solution forcing the existence of the cogenerator in the central unit;
- Case 3, optimal solution with a reduced life span for all components (15 years for absorption machines, 10 for cogenerators and boilers and 7 for compression chillers); in this case the relative weight of capital cost increases in the Objective Function;
- Case 4, optimal solution if the costs of gas and electricity were higher of 25%, decreasing the relative weight of capital cost in the Objective Function;
- Case 5, optimal solution if absorption chillers can not be installed.

Table 5: Optimization results

	Case 0	*Case 1*	*Case 2*	*Case 3*	*Case 4*	*Case 5*
Cogenerators [kW]						
Central Unit	-	-	370	-	-	-
Unit 1	-	-	-	-	-	-
Unit 2	-	1.377	1.697	1.496	1.510	656
Unit 3	-	300	-	300	300	300
Unit 4	-	300	300	300	300	300
Unit 5	-	200	-	200	200	-
Unit 6	-	-	-	-	-	-
Boilers [kW]						
Central Unit	-	-	-	-	-	-
Unit 1	518	-	-	80	-	-
Unit 2	-	-	-	-	-	-
Unit 3	686	-	-	103	-	-
Unit 4	996	376	397	203	200	755
Unit 5	516	176	-	100	218	-
Unit 6	136	-	-	-	-	-
Absorption chillers [kW]						-
Unit 1	-	-	-	-	-	-
Unit 2	-	1.700	1.700	1.700	1.700	-
Compression Chillers [kW]						
Unit 1	900	900	900	900	900	900
Unit 2	1.700	-	-	-	-	1.700
Total cogenerated electricity [MWh]	0	14.415	14.878	14.544	14.689	6.432
Total cogenerated heating [MWh]	0	16.578	16.676	16.714	16.887	7.282
Total dissipated heating [MWh]	0	~0	0	~0	27	825
Total investment cost [k€]	447	2.025	2.233	2.124	2.120	1.196
Annual investment cost [k€/y]	61	220	243	295	231	143
Purchased electricity cost [k€/y]	2.455	1.161	1.495	1.134	1.416	1.543
Sold electricity income [k€/y]	-	1.101	1.424	1.095	1.375	35
Cost of natural gas [k€/y]	226	1.772	1.725	1.783	2.240	781
Maintenance cost [k€/y]	15	328	338	331	334	153
Operating cost [k€/y]	2.695	2.160	2.161	2.153	2.616	2.433
Objective function [k€/y]	2.756	2.380	2.404	2.448	2.847	2.576
% with respect to traditional case	-	-13,65%	-12,77%	-11,19%	-17,58%	-6,55%
PBP [years]	-	5,38	6,34	6,89	3,49	1,36
TEP	3.421	4.831	5.211	4.820	4.833	2.991
CO2 Emission	9.613	13.574	14.643	13.544	13.580	4.405
PES	-	-41,21%	-52,32%	-40,89%	-41,27%	12,57%

The optimal solutions obtained in cases 1 to 4 allow the achievement of economical savings, while the CO_2 emissions increase by about 40-50%. This is due to the low EERs of the absorption chillers, especially when low temperature cooling vector is required. The PES for a simple trigeneration system obtained varying the ratio α_r (between the heat directly utilised by the users and the total cogenerated heat) can be lower than zero, if the greatest part of the cogenerated heat is sent to the absorption machines (figure 10).

$$PES = 1 - \frac{Fcog}{\frac{1}{\eta_{el}}\left(Ecog - \frac{Cabs}{COP}\right) + \frac{Hcog - Habs}{\eta_t}} \quad (36) \quad ; \quad \alpha_r = \frac{Hcog - Habs}{Hcog} \quad (37)$$

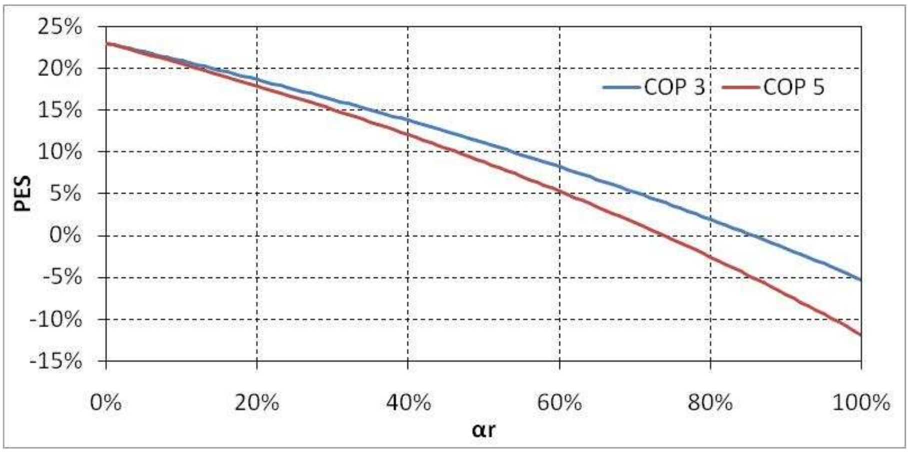

Figure 10: Primary Energy Savings vs. α_r

6 Conclusions

The model used to optimise the problem dealing with an industrial distributed trigeneration system is based on a Mixed Integer Linear Program and it helps to determine the best system configuration and operation in economical terms. Environmental benefits can also be evaluated after having determined the optimal solution. Looking at the results presented in table 5, it can be noted that optimal solutions generally include both distributed cogenerators and absorption machines, as they allow reducing the total annual cost.

Case 1: comparing it with traditional case 0, four CHP machines and an absorption chiller are installed, while only two boilers are included in the optimal solution. This global optimal solution does not include the central CHP unit, thus it reveals that in the specific application the decentralised solution is economically more convenient than the centralised one.

Case 2: forcing the existence of the central CHP unit, the objective function does not change significantly, but the pay back period increases.

Case 3: diminishing machines life span, the optimal structure does not change compared to case 1, except for the addition of some boilers. As the relative weight of investment costs increases in the optimal solution and the operation costs are almost the same, economic saving is lower.

Case 4: in a future scenario the primary energy costs are expected to increase; the optimal structure does not change with respect to the one obtained in case 1, but the results show that the economical savings are even higher compared to the conventional energy supply. Therefore the pay back period of the total investment is shorter.

Case 5: disabling the installation of absorption machines the optimal solution brings to lower economical savings with respect to the previous cases, but CO_2 emissions are reduced compared to the conventional energy supply, due to the low EERs of the absorption chillers, especially when low temperature cooling vector is required. Moreover the pay back period is lower than 2 years.

Integration through district heating micro-grids of various industrial factories, located in the same area, allows a rational utilization of available heat, so that some users can be satisfied only by the recovered heat from other production units. The effect of the thermal inertia of the grid has shown a negligible effect on the optimal structure, but has modified the optimal operation, therefore the objective function result worse by about 2%.

Nomenclature

ABS	Absorption machine	Habs	Heat required by ABS [kWh]
BOI	Boiler	Hboi	Heat produced by BOI [kWh]
Cabs	Cooling produced by ABS [kWh]	$\underline{Hboi}$, $\overline{Hboi}$	BOI load limits [kWh]
$\underline{Cabs}$, $\overline{Cabs}$	ABS load limits [kWh]	Hcog	Cogenerated heat [kWh]
Cboi', Cboi''	BOI cost [€, €/kWh]	Hdem	Heat demand [kWh]
Cbuy	Cost of purchased electricity [€/kWh]	Hin	Heat from DH network to the user [kWh]
Cch	Cooling produced by CH [kWh]	Hmax	Maximum heat transferred from the DH to the user [kWh]
$\underline{Cch}$, $\overline{Cch}$	CH load limits [kWh]	Hwas	Heat wasted[kWh]
Ccog', Ccog''	CHO cost [€, €/kWh]	invcost	Investment cost [€/year]
Cdem	Cooling energy demand [kWh]	l	Length of the DH [m]
Cgboi	Cost of fuel used in BOI [€/kWh]	Mabs	ABS maintenance cost [€/kWh]
Cgcog	Cost of fuel used in CHP [€/kWh]	Mboi	BOI maintenance cost [€/kWh]
CH	Compression chiller	Mch	CH maintenance cost [€/kWh]
CHCP	Cogenerated heat, cooling and power	Mcog	CHP maintenance cost [€/kWh]
CHP	Cogenerated heat and power	mcost	Maintenance cost [€/year]
Coabs	ABS cost [€]	opabs	ABS status
Coch	CH cost [€]	opch	COMP status
cp	Water specific heat [kJ/kg]	opcog	Cogenerator status
Csel	Price of sold electricity [€/kWh]	opcost	Operation cost [€/year]
Cwas	Cooling energy wasted [kWh]	PES	Primary energy saving
d	Diameter of the DH [m]	Qgrid	Heat stored in the DH [kWh]
DH	District heating network	Qwas	Heat wasted [kWh]
Ebuy	Purchased electricity [kWh]	sboi	BOI size [kW]
Ech	Electricity required by CH [kWh]	$\underline{sboi}$, $\overline{sboi}$	BOI size limits [kW]
Ecog	Electricity produced by CHP [kWh]	scog	CHP size [kW]
$\underline{Ecog}$, $\overline{Ecog}$	CHP load limits [kWh]	$\underline{scog}$, $\overline{scog}$	CHP size limits [kW]
Edem	Electricity demand [kWh]	t	Temperature [°C]
Esel	Sold electricity [kWh]	tground	Ground temperature [°C]
exabs	ABS existence	tmin	Min. temperature for receiving heat from the DH [°C]
exboi	BOI existence	γ	Additional decision variable
exch	CH existence	δ	Additional decision variable
excog	CHP existence	ηel	Power generation mean electric efficiency
Fboi	Fuel required by BOI [kWh]	ηt	Thermal plants mean efficiency
Fcog	Fuel required by CHP [kWh]	λ	Additional decision variable
Fobj	Objective function (annual cost) [€]	ρ	Water density [kg/m^3]

All other symbols not reported here are linearization coefficients coming from linear regressions of the equations.

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