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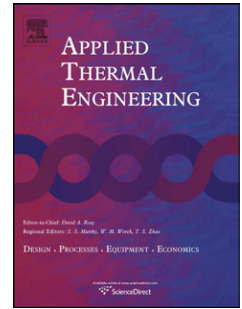


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A model for micro-trigeneration systems based on linear optimization and the Italian tariff policy

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Abstract

The influence of endogen and exogen variables on the performances of small-scale trigenerative plants is investigated by means of a simulation model where the prime mover and the other components are considered as “black boxes” characterized by their performance parameters. The operating policy of the plant is not imposed *a priori*, but it is on the contrary dynamically and automatically chosen by the model itself using linear optimization techniques. The “constitutive equations” which formalize the relationships between the plant components and the energetic and economic target functions are expressed using linear terms only. By parametrizing the characteristics of the involved machines and of the end users, such a model allows to evaluate the influence of each parameter on the performances of the whole system. The aim is to give useful indications to the manufacturers, designers and end users in the field of trigeneration. The analysis is performed at two different level of details: the first one with a simplified version of the model, for a preliminary evaluation of the influence of the most important parameters, the

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second one using the complete model, focusing the attention on the Italian situation in terms of tariffs for energy and external temperatures.

Keywords: Trigeneration CHCP, Operating policy, Linear optimization, Sensitivity analysis

1. Introduction

As no direct cycle can reach unitary efficiency, a great deal of primary energy may be “wasted” in the conversion process. When the end users require heat in addition to electric power, cogeneration (CHP - Combined Heating and Power generation) can improve the situation. In a cogenerative system, the residual heat of the conversion process is recovered for civil or industrial use. Such benefit has a price in term of complexity and cost of the plant, so that not in all cases a CHP project is economically feasible and appealing. In the field of civil applications, when the answer is negative the reason is often that the system grants a significant saving during the coldest periods only, when a lot of heat is required. Therefore, a further step can be proposed: trigenerative systems (CHCP Combined Heating Cooling Power generation, or CCHP), which are able to satisfy end users demands for electric power, heating and refrigeration and to give savings all over the year. If properly designed and realized, trigeneration offers very interesting perspectives both in general terms [1, 2] and with focus on civil [3, 4, 5, 6, 7, 8] and industrial use [9, 10]. In the most general description, a trigenerative system may be composed by a prime mover (Otto or Diesel IC engine or gas turbine) and by auxiliary machines: a boiler, compression and absorption chillers / heat pumps, bidirectional connection to the electric grid and - rarely - “hot” and

Nomenclature	
\tilde{c}_{AC}	cost of the energy given to the absorption chiller [€/kWh]
c_{FB}	cost per unit mass of the fuel used in the auxiliary boiler [€/kg]
c_{FPM}	cost per unit mass of the fuel used in the prime mover [€/kg]
\tilde{c}_{HP}	cost of the energy given to the compression heat pump [€/kWh]
c_{NGS}	average cost of the fuel supplied to the national power plants [€/kg]
\tilde{c}_{tPM}	cost of the thermal energy offered by the prime mover [€/kWh]
\tilde{c}_{WI}	cost of the power bought from the electric grid [€/kWh]
\tilde{c}_{WO}	cost of the power sold to the electric grid [€/kWh]
COP_{HP}	coefficient of performance of the compression heat pump [-]
\dot{C}_{conv}	total cost of the conventional system [€/h]
\dot{C}_{trigen}	total cost of the trigeneration system [€/h]
\dot{C}_{target}	target cost of the trigeneration system including storage [€/h]
\dot{E}_{conv}	total primary energy consumption of the conventional system [kW]
\dot{E}_{trigen}	total primary energy consumption of the trigeneration system [kW]
LHW_F	lower heating value of the fuel [kJ/kg]
$L.O.L$	lower operating limit [kW]
\dot{M}_{FB}	fuel mass flow rate to the auxiliary boiler [kg/s]
\dot{M}_{FPM}	fuel mass flow rate to the prime mover [kg/s]
$\dot{Q}_{\rightarrow EU}$	end users demand for heat supply [kW]
$\dot{Q}_{\leftarrow EU}$	end users demand for heat removal [kW]
$\dot{Q}_{AC\leftarrow CS}$	thermal power from the “cold” storage system to the absorption chiller [kW]
$\dot{Q}_{CS\leftarrow EU}$	thermal power from the end users to the “cold” storage system [kW]
$\dot{Q}_{HP\leftarrow CS}$	thermal power from the “cold” storage system to the heat pump [kW]
$\dot{Q}_{HS\rightarrow EU}$	thermal power from the “hot” storage system to the end users [kW]
\dot{Q}_{PM}	total thermal power produced by the prime mover [kW]
$\dot{Q}_{PM\rightarrow AC}$	thermal power from the prime mover to the absorption chiller [kW]
$\dot{Q}_{PM\rightarrow EU}$	thermal power from the prime mover to the end users [kW]
$\dot{Q}_{PM\rightarrow HS}$	thermal power from the prime mover to the “hot” storage system [kW]
$\dot{Q}_{PM\ diss}$	thermal power produced by the prime mover and not used [kW]
\dot{Q}_R	generic cooling exchange [kWh]
\dot{Q}_S	generic heating exchange [kWh]
RMF	reverse metering factor [-]
$SCFP\%T/C$	saving from the energetic point of view [-]
$SEUR\%T/C$	saving from the economic point of view [-]
T	temperature [°C]
\dot{W}	generic electric power exchange [kW]
$\dot{W}_{\rightarrow EU}$	end users demand for electric power [kW]
$\dot{W}_{GR\rightarrow EU}$	power from the electric grid to the end users [kW]
$\dot{W}_{GR\rightarrow HP}$	power from the electric grid to the compression heat pump [kW]
\dot{W}_{PM}	total electric power produced by the prime mover [kW]
$\dot{W}_{PM\%}$	percentile electric power load of the prime mover [-]
$\dot{W}_{PM\rightarrow GR}$	power from the prime mover to the electric grid [kW]
ε_{AC}	efficiency of the absorption chiller [-]
ε_{CC}	efficiency of the compression chiller [-]
η_{tPM}	electrical efficiency of the prime mover [-]
η_{GR}	total (conversion and distribution) efficiency of the national power system [-]
η_B	thermal efficiency of the boiler [-]
η_{tPM}	thermal efficiency of the prime mover [-]
ρ_E	maximum peak of power demand over prime mover rated power [-]
Subscripts	
MAX	maximum achievable value
MIN	minimum achievable value
REF	reference or rated values, operation at ISO conditions

“cold” storage systems. It is therefore more complex and expensive than a CHP system, consequently a very accurate techno-economical analysis is even more important. The increased complexity of the system reflects also in a higher difficulty of such analysis: there are truly many variables to be considered. Among them, the most critical are the end users needs and the operating policy. The demands should be accurately known in terms of peak values and shape, hour per hour along the day and the year. The operating policy has for a long time been fixed “a priori”, bounding the system to satisfy the electric or the heat requests of the users. Such a choice may often be non-optimal; therefore many works started to be devoted to the optimization of the operating policy. In general, two different viewpoints are adopted: some studies analyse the system and its components in great detail [11, 12, 13], while the optimization technique in itself is not very sophisticated; in other papers the main focus is on the mathematics of optimization [14, 15, 16, 17, 18] with a minor description of the system from an engineering point of view. Recently, a few research groups proposed extended analyses including environmental and legal constraints, together with the use of storage systems [19, 20, 21, 22, 23, 24, 25], still with a major focus on the mathematical model. Scope of this work is to perform an analysis at an intermediate level: system components are seen as “black boxes” characterized by their operational parameters (efficiencies, operating limits, COPs) whose dependence from the operating conditions (temperatures, loads) is formalized by means of equations which contain the technological information. The results should also offer some guidelines to set a relative scale of importance among the single machine parameters (efficiencies of the primary and

auxiliary machines, operational limits, ...).

2. Simulation code

Core of the simulation code is the formalization of a linear programming problem constituted by:

- a target function to be minimized, consisting of the primary energy consumption \dot{E}_{trigen} or operational cost \dot{C}_{trigen} . The choice of the operational instead of the total cost or NPV is due to the fact that the maintenance cost heavily depends on the maintenance policies and costs, while the costs of the machines is rapidly varying as an effect of the technological improvements;
- the bounds:
 - the energy exchanges among the plant components;
 - the dependence of the components parameters on the operating conditions. The technological specificities of the components intervene here.

Using this approach, the code remains for the most part independent of the component specificities, so that changes can be easily introduced both in the single components and in the system configuration.

3. System architecture and model

The two system architectures which will be used for the analysis are both based on a micro gas turbine as the prime mover, due to the fact that distributed generation appears to be a very promising field for CHCP and micro

gas turbines may be an appealing technology for properly designed applications [26]. The system architectures and the energy exchanges between the components for the simplified and complete cases are represented in Fig. 1. The “conventional plant” configuration which is the term of comparison is constituted by a boiler, an electric compression chiller for cooling and a one-directional connection to the electric grid. In the case of the “conventional plant” the energy exchanges are very simple: power goes from the electric grid to the end users and to the electric chiller. The latter satisfies the cooling needs of the end users, while fuel is supplied to the boiler which gives heat to the end users.

4. Simplified version

For the simplified case, the two target functions can be expressed as follows:

- energetic point of view:

$$MIN: \dot{E}_{trigen} = \left(\dot{M}_{FPM} + \dot{M}_{FB} \right) \cdot LHW_F + \frac{\dot{W}_{GR \rightarrow EU} + \dot{W}_{GR \rightarrow HP} - \dot{W}_{PM \rightarrow GR}}{\eta_{GR}} \quad (1)$$

- economic point of view (on an hourly basis, which was chosen for coherence with the Italian tariff policy used in the refined version of the

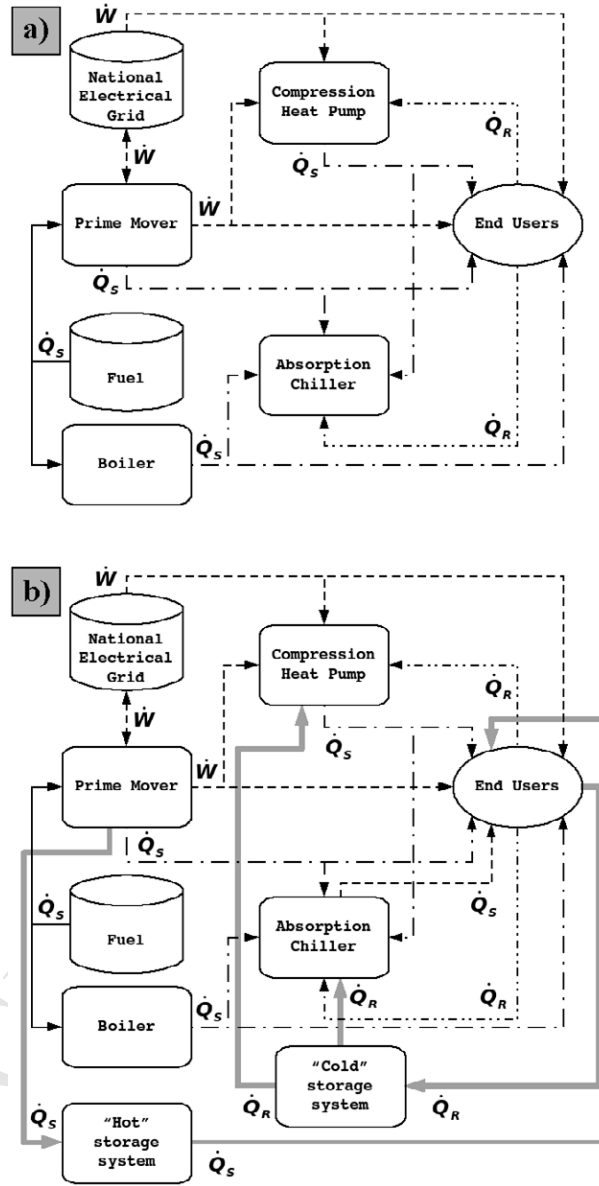


Figure 1: Simplified (a) and complete (b) system architectures.

model):

$$\begin{aligned}
 MIN: \dot{C}_{trigen} = & c_{FPM} \cdot \dot{M}_{FPM} \cdot 3600 + \\
 & + c_{FB} \cdot \dot{M}_{FB} \cdot 3600 + \\
 & + \tilde{c}_{WI} \cdot (\dot{W}_{GR \rightarrow EU} + \dot{W}_{GR \rightarrow HP}) + \\
 & - \tilde{c}_{WO} \cdot \dot{W}_{PM \rightarrow GR}
 \end{aligned} \tag{2}$$

In Italy, due to different taxes, $c_{FPM} \neq c_{FB}$. The non-SI unit [kWh] is conserved for some of the quantities because it is very convenient to use when performing a hourly-based analysis. $\tilde{c}_{WO} / \tilde{c}_{WI}$ is called “reverse metering factor” *RMF* and is always lower than 1.

For the conventional system there is nothing to optimize and the system just has to satisfy the end users demands:

$$\dot{E}_{conv} = \frac{\dot{W}_{\rightarrow EU}}{\eta_{GR}} + \frac{\dot{Q}_{\rightarrow EU}}{\eta_{tB}} + \frac{\dot{Q}_{\leftarrow EU}}{\varepsilon_{CC} \cdot \eta_{GR}} \tag{3}$$

From the economic point of view:

$$\begin{aligned}
 \dot{C}_{conv} = & \dot{W}_{\rightarrow EU} \cdot \tilde{c}_{WI} + \frac{\dot{Q}_{\rightarrow EU}}{\eta_{tB} \cdot LHV_F} \cdot c_{FB} \cdot \\
 & \cdot 3600 + \frac{\dot{Q}_{\leftarrow EU}}{\varepsilon_{CC}} \cdot \tilde{c}_{WI}
 \end{aligned} \tag{4}$$

$\dot{W}_{\rightarrow EU}$ is the net power demand of the end users for their direct use, it does not include the requests of the compression chiller.

In both energetic and economic cases the constraints which must be respected in the search for the optimum solution are the satisfaction of the end users demands, the respect of the operating limits of the plant components, the

relationships among the energy quantities entering or leaving each component and the non-negativity (which is required both from the mathematical and the physical points of view) of all variables apart from the savings. As an example, the constraints on the prime mover are the following:

$$\begin{aligned}
\dot{W}_{PM} &\leq \dot{W}_{PM MAX} \\
\dot{W}_{PM} &\geq \dot{W}_{PM MIN} \\
\dot{Q}_{PM} &\leq \dot{Q}_{PM MAX} \\
\dot{Q}_{PM} &\geq \dot{Q}_{PM MIN} \\
\dot{W}_{PM} &= \eta_{ePM} \cdot \dot{M}_{FPM} \cdot LHV_F \\
\dot{W}_{PM} &= \dot{W}_{PM \rightarrow EU} + \dot{W}_{PM \rightarrow HP} + \dot{W}_{PM \rightarrow GR} \\
\dot{Q}_{PM} &= \eta_{tPM} \cdot \dot{M}_{FPM} \cdot LHV_F \\
\dot{Q}_{PM} &= \dot{Q}_{PM \rightarrow EU} + \dot{Q}_{PM \rightarrow AC} + \dot{Q}_{PM diss}
\end{aligned} \tag{5}$$

$\dot{Q}_{PM diss}$ has to be dissipated due to the fact that the simplified model does not include heat storage systems.

All constraints are expressed in terms of powers, so that the optimal operating policy can be determined on an arbitrary time interval, within the limit that the loads and the operational parameters can be considered constant on such interval.

Input data for the calculation are: the end users demands in terms of electric power, heating and cooling; the operational parameters of the components (efficiencies plus minimum and maximum loads, all varying with ambient conditions); fuel characteristics (LHV_F) and, for the economic optimization, fuel and electrical tariffs. The values reported in Tab. 1, referring to machines operating at ISO conditions, were chosen as reference values for the sensitivity

Parameter	Value	Units
$COP_{HP REF}$	3.00 / 2.50	-
LHV_F	48327	kJ/kg
$\dot{Q}_{PM MAX}$	170	kW
RMF	0.75	-
$\dot{W}_{PM MAX}$	100	kW
$\dot{W}_{PM MIN}$	50	kW
$\varepsilon_{AC REF}$	0.70	-
η_{GR}	0.38	-
$\eta_{ePM REF}$	0.30	-
$\eta_{tB REF}$	0.80	-
$\eta_{tPM REF}$	0.50	-

Table 1: Reference values for the input parameters. $COP_{HP REF}$ is fixed at 3.00 when used as a heat pump, 2.5 when used as a refrigerating unit.

analysis. For different conditions and for operation at partial loads, the values of the main parameters are corrected using simplified (mainly polynomial) empirical relationships obtained by interpolation on real data.

From the economic point of view, the tariff system for gas and electric energy has a primary impact. In the simplified model a rough simplification of the Italian tariff policy is used, based on four tariff levels l for power (level 1

corresponds to the higher cost):

$$\begin{aligned}
 \tilde{c}_{WI}(l) &= c_1 \cdot l^{c_2} \\
 \tilde{c}_{WO}(l) &= RMF \cdot \tilde{c}_{WI} \\
 c_{FPM} &= c_3 \cdot \tilde{c}_{WI}(1) \\
 c_{FB} &= c_4 \cdot c_{FPM}
 \end{aligned} \tag{6}$$

all of them in [c€/kWh], where $c_1 = 12$ c€/kWh, $c_2 = -0.6$ [-], $c_3 = 0.3$ [kWh/kg] and $c_4 = 4/3$ [-].

5. Refined version

In the complete system the absorption chiller is considered invertible too and “hot” and “cold” storage systems are introduced. The dependence of the operating parameters from the temperature is refined, using the real temperatures of a location near Milan, in Italy, and the real Italian policy is introduced as the tariff scenario.

5.1. Modifications in the constraints and in the target functions

The relationships giving the dependency of the prime mover parameters from temperature and loads were refined considering real data. The attention was focused on gas turbines within the field $\dot{W}_{PM} \leq 500$ kW. A series of power and efficiency curves from different manufacturers were found and interpolated using polynomial forms, for example:

$$\begin{aligned}
 \eta_{ePM}(T) &= (c_5 + c_6 \cdot \dot{W}_{PM}) \cdot T^2 + (c_7 + c_8 \cdot \\
 &\quad \cdot \dot{W}_{PM}) \cdot T + (c_9 + c_{10} \cdot \dot{W}_{PM})
 \end{aligned} \tag{7}$$

where T is the temperature [$^{\circ}\text{C}$] and the coefficients c_i were obtained by regression.

Both compression and absorption heat pumps are hypothesized to be invertible, but obviously they cannot satisfy both heating and cooling demand contemporarily. As no Boolean variable can be introduced to preserve the linearity of the model, the optimization process (which will be described in Section 6) is run three times for the spring and summer periods, when both heating and cooling demands are present. By means of apposite coefficients introduced in the constraints, a first run is done forcing both components to offer cooling potentiality, a second one forcing the compression unit to function as a heat pump and the absorption unit as a chiller, a third one inverting such roles. The three “optimums” are compared and the best one is chosen as the true optimum.

“Hot” and “cold” storage systems are introduced as “ideal” ones, with neither lower nor higher limit to their capacity or to their flexibility of use. Using them the system can store resources (for example hot water to store thermal energy and ice or cold water to store cooling potentiality) during the periods in which the end users demands do not saturate the prime mover capability. Such resources are then used in the following periods, thus reducing the total consumption of primary energy. As storage systems are not very diffused in real systems, the refined model was prepared in two versions, one with storage systems and the other without them, to be able to perform analyses on both cases. The introduction of storage systems forces to change the target functions too, due to the fact that in their original form there is nothing that invites the model to store energy instead of dissipating it. A

suitable modified economic target function is as follows:

$$\begin{aligned}
\dot{C}_{target} = & \left(c_{FPM} \cdot \dot{M}_{FPM} + c_{FB} \cdot \dot{M}_{FB} \right) \cdot 3600 + \\
& + \tilde{c}_{WI} \cdot \left(\dot{W}_{GR \rightarrow EU} + \dot{W}_{GR \rightarrow HP} \right) + \\
& - \tilde{c}_{WO} \cdot \dot{W}_{PM \rightarrow GR} + \\
& + c_{11} \cdot \tilde{c}_{tPM} \cdot \left(\dot{Q}_{PM \rightarrow HS} - \dot{Q}_{HS \rightarrow EU} \right) + \\
& + c_{12} \cdot \frac{\tilde{c}_{AC} + \tilde{c}_{HP}}{2} \cdot \left(\dot{Q}_{AC \leftarrow CS} + \right. \\
& \left. + \dot{Q}_{HP \leftarrow CS} - \dot{Q}_{CS \leftarrow EU} \right)
\end{aligned} \tag{8}$$

The last two terms are not real costs, the total cost remains \dot{C}_{trigen} which is calculated in the post-processing phase and which includes the first three terms only, as in the case without storage systems. The added terms serve only to guide the model towards a properly weighted use of the storage systems.

\tilde{c}_{tPM} can be calculated as $\tilde{c}_{tPM} = 1/\eta_{tPM} \cdot c_{FPM}/LHV_F \cdot 3600$; c_{11} [-] and c_{12} [-] are two coefficients whose value has to be lower than 1 (it was fixed to 0.8 here) to keep in account the effects of dissipations, storage costs, etc. on the value of the stored energy. \tilde{c}_{AC} has to be calculated considering the real costs of the energy used in the absorption chiller, using a simple arithmetic average:

$$\tilde{c}_{AC} = \frac{c_{FPM} + c_{FB} + c_{NGS}}{3} \cdot \frac{1}{LHV_F} \cdot 3600 \tag{9}$$

The value of c_{NGS} was fixed to 0.2256 €/kg [27].

5.2. The tariff policy

The Italian tariff system is very complex, both for the natural gas (which is the fuel supplied to the prime mover and to the boilers) and, particularly, for electric energy acquired from / exported to the grid. The detailed description of the tariffs can be found on institutional or distributors Web sites. Figure 2 shows a scheme of the different components that constitute the tariff for the purchase of electric energy from the grid. The most important aspects for the present work are that the tariffs depend on the consumption (with an impact on the optimization process described in the following) and that the power tariffs are different hour per hour during the day (the already cited four-level tariff system) and also between working and festival days.

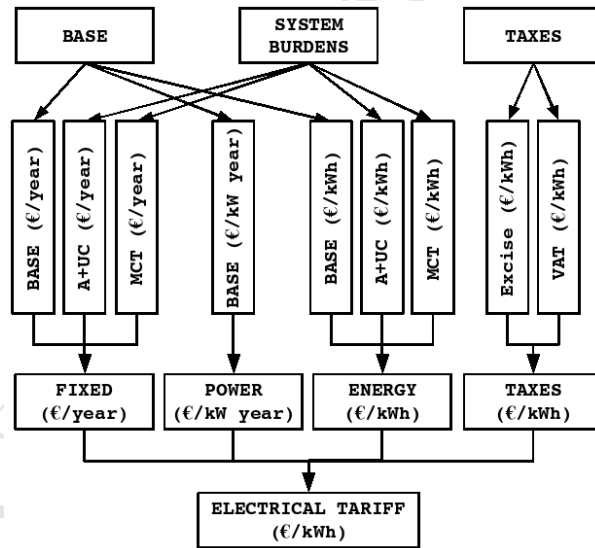


Figure 2: Scheme for the calculation of the Italian tariff for the purchase of electric energy.

5.3. Temperatures

The operating parameters of the system components depend on the external temperature, so the prediction of the latter is very important for a significant analysis. Data on the hourly temperatures near Milan (Italy) were acquired from the Biometeolab Centre of the University of Milan for the years 2003-05 and used in season-averaged terms as a part of the “typical days” identification process.

5.4. Typical days

As a compromise between accuracy, data availability and easiness of use of the model, a conventional “typical days” approach is chosen to reduce the number of time periods on which the optimization is performed. Ten “typical days” (Tab. 2) were identified on the basis of the temperature conditions, the distinction between working and festival days in the tariffs and the end users demands.

Code	Period	N. in 1 year
WW1	working days from 01-09 to 03-14 (winter)	47
FW2	festival days from 12-19 to 03-14 (winter)	39
WM1	working days from 03-15 to 04-28 (spring 1)	30
WM2	working days from 04-29 to 06-16 (spring 2)	33
FM1	festival days from 03-15 to 06-16 (spring)	31
WS1	working days from 06-17 to 09-30 (summer)	65
FS1	festival days from 06-17 to 09-30 (summer)	41
WA1	working days from 10-01 to 11-30 (autumn 1)	43
WA2	working days from 12-01 to 12-18 (autumn 2)	11
FA1	festival days from 10-01 to 12-18 (autumn)	25

Table 2: “Typical days” along the year.

6. Optimization algorithm

The model and algorithm were implemented using the *Matlab*[®] programming environment and the optimization step in itself is deputised to the built-in function *linprog*, which solves the problem using a primal-dual method. Before the first run, fixed input data (hour of the day, electrical tariff level, ambient conditions and users demands) are loaded. Then a pre-processing step is needed to calculate the variable input, for which information is needed about the system loads (for the efficiencies) and total consumptions (for the tariffs). “First try” values are given, optimization is performed, and all the non-fixed inputs are re-calculated using its results. The two steps are iterated until the differences in the outputs from two successive loops goes under a chosen value.

A hourly basis is chosen as the time period for optimization, because it gives a sufficient level of detail and it is coherent with the Italian tariff policy. The results for each period are joined together to give the results on each “typical day” and then on a whole year.

When storage systems are included, the content of each of them at the i^{th} iteration is passed as an input for the $(i + 1)^{th}$ iteration. Due to this implementation of the algorithm, the use of the storage systems is not truly optimized over all the day / year: in each period the algorithm does its best using the storage system content in that period; from a global perspective the storage policy is therefore managed following a sort of greedy algorithm. The optimum results are compared with the results using the conventional system so that the energy and money savings can be evaluated. The trigeneration system is a superset of the conventional system, therefore the saving

should always be positive or at most zero. When that does not happen and the calculated savings are negative, the cause is the impossibility for the model to stop the prime mover in the optimization phase due to the constraints involving the lower operating limit. Such distortion is corrected in the post-processing phase. During the same step, modifications of the optimum solution can also be introduced, if the calculated optimum should not be technologically viable (for example if it should request too frequent start & stops of the prime mover).

7. End users

The correct evaluation of the end users demands is one of the core aspects for the analyses, but at the same time it is one of the hardest tasks. Finding or estimating detailed and reliable data on $\dot{W}_{\rightarrow EU}$, $\dot{Q}_{\rightarrow EU}$ and in particular $\dot{Q}_{\leftarrow EU}$ is very difficult. *Ad hoc* measurements would be the best solution [28], but it would also be a very long activity, due to the need to average the data over at least a few years. Data on five end users of different types (“Hospital”, “Hotel”, “Office building”, “Sporting center”, “Trading center”) were therefore taken from literature [29] and partially extended and adapted to make them suitable to test the optimization software and to perform a sensitivity analysis on the system main parameters. For each “typical day” the information about the averaged demands was splitted in maximum values and hourly dimensionless profiles (hour per hour, demand over maximum demand for that “typical day”). This makes it possible to study the influence of the profile and of the size separately.

8. Results

In the following, results will be presented and compared with a few literature indications. It is practically the only viable validation of the model, apart from the trivial check of comparing the calculated “optimal” operating policy to other ones which were arbitrarily chosen. The mathematics of the optimization step was out of the scope of our work, so the built-in *Matlab*[®] functions were trusted. In fact an optimization model in the trigeneration field cannot be truly validated against some benchmark cases for which a well-known solution exists. Up to our best knowledge, no reference model has been developed up to now too. As for comparison with experimental data, it would be first of all necessary a statistically significant number of data sets about experimental cases, all homogeneous in terms of “boundary conditions” (end users demands, climate conditions, costs and tariffs) and served by trigenerative plants operating upon different policies. Such data sets does not seem to be available. Moreover, such comparison would give a true answer only if some of the experimental operating policy should be better than the one proposed by the model; otherwise, the model “wins a battle”, but in theory another, better, policy could still be found.

8.1. Results of the first level of analysis

The first investigated parameter was the ratio ρ_E between the maximum peak of power demand and the prime mover rated power. Figure 3 show the results expressed as per cent savings during one year for the “office building” end user. The annual per cent saving is calculated as a weighted average of the single “typical day” savings on the yearly distribution of “typical days”.

From the energetic point of view the saving is expressed by means of the $S_{CFP\%} T/C$ parameter, defined as:

$$S_{CFP\%} T/C = 100 \cdot \left(1 - \frac{\text{trigenerative fuel consumption}}{\text{conventional fuel consumption}} \right) \quad (10)$$

while from the economic point of view the saving parameter is $S_{EUR\%} T/C$ defined as:

$$S_{EUR\%} T/C = 100 \cdot \left(1 - \frac{\text{trigenerative operating cost}}{\text{conventional operating cost}} \right) \quad (11)$$

ρ_E was varied from 0.1 to 10, the values of the other parameters were kept at their reference value (Tab. 1). The curves do not pass through the origin of

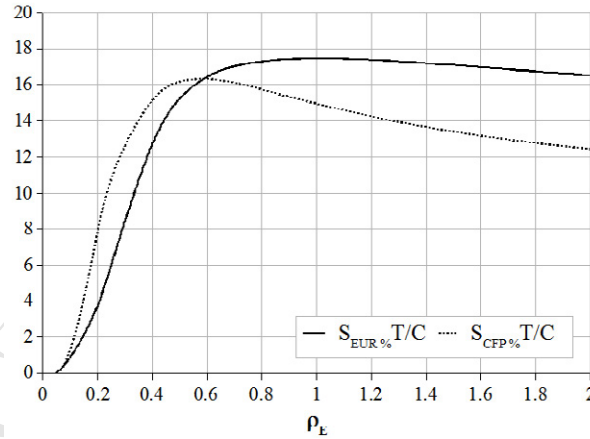


Figure 3: Office building: Annual % saving trigenerative vs. conventional solution as a function of the ratio between the maximum peak of power demand and the prime mover rated power.

the coordinate system: when the prime mover rated power and its $\dot{W}_{PM MIN}$

grow too much, the use of the trigeneration plant is not competitive and consequently there are no savings. This effect rapidly decreases with the growth of the end users power demand (steep rise in the left part of the curves). At higher values of ρ_E , it becomes necessary to get more and more energy from the grid and the boiler, so that the savings tends to zero for ρ_E going to infinity.

Subsequently, fixing ρ_E to its optimum value, the influence of the other main parameters of the plants components was studied each time varying only one of them while keeping the other to their reference values. For these analyses too, the results are expressed by annual per cent saving; results from the energetic point of view are shown in Fig. 4 for the “Trading centre”. The economic point of view gives similar results. It can be seen how η_{ePM} has the most relevant influence on the savings: with the same fuel consumption, its growth grants more power for the end users, the invertible compression heat pump or the grid. On the contrary, a higher η_{tPM} involves two opposite effects: on the one hand it means more heat to feed the chilling unit (provided that the thermal levels are compatible) thus reducing the use of the auxiliary boiler; on the other hand there may be higher redundancy of thermal energy. The lower operating limit (*L.O.L.*) has a very slight impact on the saving. Concerning the cooling machines, the energy saving falls down when the COP_{HP} (which is shown in the dimensionless form COP_{HP}/COP_{HPREF} in Fig. 4) grows. At low COP_{HP} s the cooling needs are better satisfied using the absorption chiller, while at higher COP_{HP} s such an advantage quickly decreases because the use of compression heat pump becomes very cheap, so that trigenerative and conventional plants both use electricity to satisfy

the cooling demand. On the contrary, the satisfaction of the heating load by means of a heat pump is an advantage for the trigenerative plant especially at high COP_{HPs} , because it becomes increasingly favourable compared to the conventional boiler. Such two opposite effects cause a stationary point (a minimum) in the $S_{CFP\%} T/C = f(COP_{HP}/COP_{HPREF})$ curve, but it appears in an interval of COP_{HP}/COP_{HPREF} values which is meaningless from the technological point of view. For real plants the first effect only is significant. Figure 5 shows $S_{EUR\%} T/C$ as a function of RMF and c_{FPM}/\tilde{c}_{WI} (1). This points out the influence of the tariffs policy on the economic appeal of a trigenerative plant. It is evident the importance of the fuel/electric energy cost ratio, while the RMF is significant only when the previous is low.

9. Results of the second level of analysis

At the refined level of analysis some results are confirmed, while others change - particularly the ones which are strongly dependent on the tariffs. Due to the fact that the storage systems are not very diffuse, results using the model without them will be presented first. Figures 6 and 7 show two examples which evidence in hourly terms the influence of η_{ePM} and c_{FPM} on the economic saving. The independent parameters are varied from 80% to 120% of their reference values. The cost of the trigeneration plant decreases very much in consequence of an improvement in the prime mover electric performance when the end user demands implies an high load of the same. This is reasonable and not surprising and it confirms the results of the first level of analysis. The saving is much lower when the prime mover is kept at its *L.O.L.* just to avoid the plant turning off. The trend is different from the

one evidenced in the first level analysis, showing how the improvement due to η_{ePM} is strongly dependent on the tariffs. Therefore, forcing the improvement of η_{ePM} is not a choice which always gives a high payback. Fixed η_{ePM} , the importance of the η_{hPM} variations is definitely lower and it will not be shown here. Concerning c_{FPM} , results are presented for two particularly significant “typical days”. In *WW1* the very high heating demand forces to use the auxiliary boiler to satisfy the thermal load, so that the variations in c_{FB} has a considerable impact on the total trigenerative costs; during *FM1* the thermal needs are on the contrary much lower and c_{FB} variations are almost negligible. The correct analysis should also include the conventional plant cost variation, but for simplicity in Fig. 7 the fuel to the conventional plant is priced at its reference value. Conventional plant cost is always higher than trigenerative one, even when considering the lowest and the highest costs respectively. Trigeneration would therefore remain the less expensive solution also in a coming tariffs rise. Figure 8 shows the annual saving when varying independently c_{FPM} or c_{FB} . Such results indicate that a possible facilitation for trigenerative plants could be a tariff decrease for the fuel destined to the prime mover, since in similar cases the savings may reach about 45%. To finish where we started, the last investigated parameter was ρ_E , which has a particular importance for an investment analysis. Moreover, some literature results are available for a comparisons. In all cases the hour-per-hour analysis brings to the conclusion that an oversized prime mover would be useful during winter only. Moving to the yearly-based analysis, the annual % savings are shown in Fig. 9 for the “Hotel” and “Hospital” end user. The first-level results for the “Office building” are also shown. It can be noticed

the very good agreement in the trend between the latter and the “Hotel”, from both points of view. From the economic point of view, the second-level analysis shows a sort of an “M-shaped” curve, at an embryonic stage for the “Hotel” case while it is very pronounced in the “Hospital” case. Considering both the end users, the optimum ρ_E is around 1.2, which is in discreet agreement with literature [13] that reports an optimum value for $1/\rho_E$ around 0.7. Concerning the system with storage systems, an example of cost trend for trigenerative vs conventional plants is shown in Fig. 10, which presents a sort of “summary” including results from the models with storage, without storage and from the conventional one. The storage systems have a beneficial effect on energy savings, thus giving a long-term benefit (lower primary energy consumption) and directly an economic advantage: in fact the software makes choices which differ from the case without storage systems, particularly trying to restrict the use of the auxiliary boiler (because the feeding fuel is more expensive).

10. Conclusions

A model for automatic optimization, with no aprioristic hypothesis, of the operating policy of trigenerative plants was developed and implemented. The plants are modelled as a set of “black boxes” representing the system components by means of their performance parameters. Relationships between the plant components and target functions were kept linear, so that linear techniques can be used to perform the optimization. The model was developed in a simplified and in a complete version and sensitivity analyses were performed using both of them, to highlight the influence of endogen

and hexogen variables on the energetic and economic appeal of a trigenerative plant. The implemented optimization software can already be a useful instrument for designers and stakeholders of trigenerative plants. Further improvements of the code may deal with: the inclusion of operation and maintenance costs, externalities, management costs, etc., and also the automatic calculation of payback time, investment indicator, etc., if desired; the introduction of a database collecting several types of prime movers, with their main technical/economic features, to leave the software free to optimize also the choice of the prime mover itself, and the evaluation of the environmental plant performances, setting up a detailed analysis about emissions; the inclusion of the storage system truly within the optimization process, moving from a hourly-based to a daily-based optimization.

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References

- [1] G. Temir, D. Bilge, Thermo-economic analysis of a trigeneration system, *Applied Thermal Engineering* 24 (2004) 2689-2699.
- [2] E. Cardona, A. Piacentino, A methodology for sizing a trigeneration plant in mediterranean areas, *Applied Thermal Engineering* 23 (2003) 1665-1680.
- [3] K.C. Kavvadias, A.P. Tosios, Z.B. Maroulis, Design of a combined heating, cooling and power system: Sizing, operation strategy selection and

- parametric analysis, *Energy Conversion and Management* 51(4) (2010) 833-845.
- [4] N. Sugiarta, S.A. Tassou, I. Chaer, D. Marriott, Trigeneration in food retail: An energetic, economic and environmental evaluation for a supermarket application, *Applied Thermal Engineering*, 29(13) (2009) 2624-2632.
- [5] A. Arteconi, C. Brandoni, F. Polonara, Distributed generation and trigeneration: Energy saving opportunities in Italian supermarket sector, *Applied Thermal Engineering*, 29(8-9) (2009) 1735-1743.
- [6] L. Lin, Y. Wang, T. Al-Shemmeri, T. Ruxton, S. Turner, S. Zeng, J. Huang, Y. He, X. Huang, An experimental investigation of a household size trigeneration, *Applied Thermal Engineering* 27 (2007) 576-585.
- [7] E. Cardona, A. Piacentino, F. Cardona, Energy saving in airports by trigeneration. Part I: Assessing economic and technical potential, *Applied Thermal Engineering* 26 (2006) 1427-1436.
- [8] D. Ziher, A. Poredos, Economics of a trigeneration system in a hospital, *Applied Thermal Engineering* 26 (2006) 680-687.
- [9] P. Colonna, S. Gabrielli, Industrial trigeneration using ammonia-water absorption refrigeration systems (AAR), *Applied Thermal Engineering* 23 (2003) 381-396.
- [10] J. Bassols, B. Kuckelkorn, J. Langreck, R. Schneider, H. Veelken, Trigeneration in the food industry, *Applied Thermal Engineering* 22 (2002) 595-602.

- [11] J. Godefroy, R. Boukhanouf, S. Riffat, Design, testing and mathematical modelling of a small-scale CHP and cooling system (small CHP-ejector trigeneration), *Applied Thermal Engineering* 27 (2007) 68-77.
- [12] S. Campanari, E. Macchi, Technical and tariff scenarios effect on microturbine trigenerative applications, *ASME Journal of Engineering for Gas Turbines and Power* 126 (2004) 581-589.
- [13] S. Campanari, L. Boncompagni, E. Macchi, Microturbines and trigeneration: optimization strategies and multiple engine configuration effects, *ASME Journal of Engineering for Gas Turbines and Power* 126 (2004) 92-101.
- [14] G. Chicco, P. Mancarella, Matrix modelling of small-scale trigeneration systems and application to operational optimization, *Energy*, 34(3) (2009) 261-273.
- [15] A. Rong, R. Lahdelma, P.B. Luh, Lagrangian relaxation based algorithm for trigeneration planning with storages, *European Journal of Operational Research* 188 (2008) 240-257.
- [16] P. Arcuri, G. Florio, P. Fragiaco, A mixed integer programming model for optimal design of trigeneration in a hospital complex, *Energy* 32 (2007) 1430-1447.
- [17] A. Rong, R. Lahdelma, An efficient linear programming model and optimization algorithm for trigeneration, *Applied Energy* 82 (2005) 40-63.
- [18] J.-J. Wang, Y.-Y. Jing, C.-F. Zhang, G.-H. Shi, X.-T. Zhang, A fuzzy

- multi-criteria decision-making model for trigeneration system, *Energy Policy*, 36(10) (2008) 3823-3832.
- [19] P.J. Mago, L.M. Chamra, J. Ramsaya, Micro-combined cooling, heating and power systems hybrid electric-thermal load following operation, *Applied Thermal Engineering*, 30 (8-9) 2010 800-806.
- [20] M.A. Lozano, J.C. Ramos, L.M. Serra, Cost optimization of the design of CHCP (combined heat, cooling and power) systems under legal constraints, *Energy* 35 (2010) 794-805.
- [21] S.M. Lai, C.W. Hui, Integration of trigeneration system and thermal storage under demand uncertainties, *Applied Energy* 87(9) (2010) 2868-2880.
- [22] K.C. Kavvadias, Z.B. Maroulis, Multi-objective optimization of a trigeneration plant, *Energy Policy*, 38 (2) 2010, 945-954.
- [23] P.J. Mago, L.M. Chamra, Analysis and optimization of CCHP systems based on energy, economical, and environmental considerations, *Energy and Buildings* 41 (2009) 1099-1106.
- [24] H. Cho, P.J. Mago, R. Luck, L.M. Chamra, Evaluation of CCHP systems performance based on operational cost, primary energy consumption, and carbon dioxide emission by utilizing an optimal operation scheme, *Applied Energy* 86 (2009) 2540-2549.
- [25] M.A. Lozano, M. Carvalho, L.M. Serra, Operational strategy and marginal costs in simple trigeneration systems, *Energy* 34 (2009) 2001-2008.

- [26] C. Invernizzi, P. Iora, P. Silva, Bottoming micro-Rankine cycles for micro-gas turbines, *Applied Thermal Engineering* 27 (2007) 100-110.
- [27] BP Plc, Data for the year 2005, September 2006 <www.bp.com> accessed 15.09.2006
- [28] E. Cardona, A. Piacentino, A measurement methodology for monitoring a CHCP pilot plant for an office building, *Energy and Buildings* 35 (2003) 919-925.
- [29] E. Macchi, S. Campanari, P. Silva, *Natural gas microcogeneration*, Polipress, Milan, Italy, 2005 (the book is written in Italian - original title: *La microcogenerazione a gas naturale*).

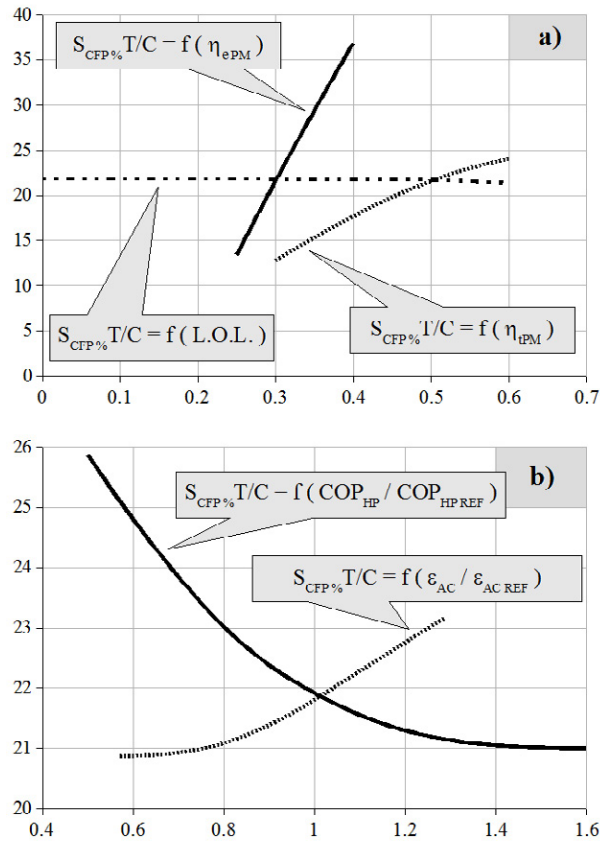


Figure 4: Trading center: annual % saving trigenerative vs. conventional solution, optimizing the energetic aspect and varying: (a) the prime mover efficiencies and lower operating limit (expressed as ratio to the rated operating power), (b) the cooling machines performance parameters.

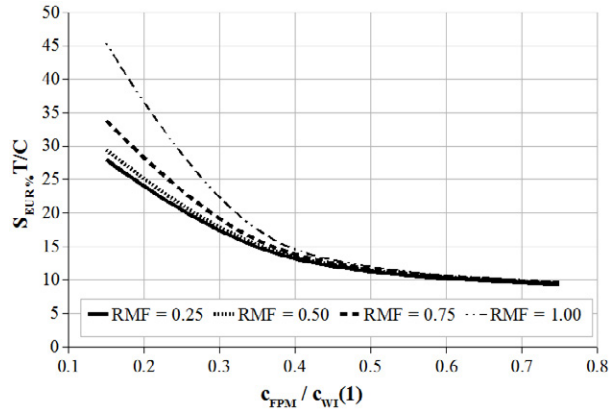


Figure 5: Office building: annual % saving trigenerative vs. conventional plant, economical optimization varying RMF and fuel/electric energy cost.

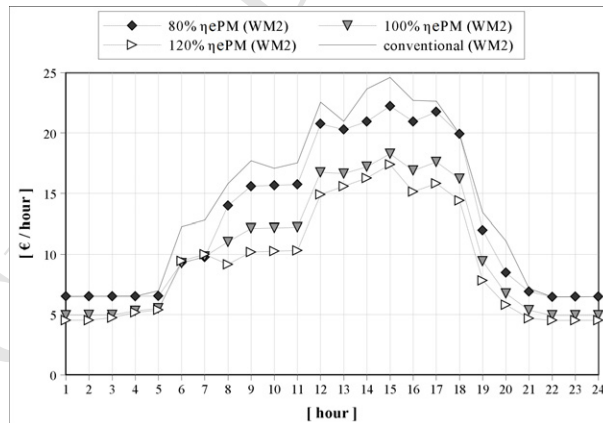


Figure 6: Office building: hourly operating cost for the trigenerative and conventional plants when varying the prime mover electric efficiency during typical day *WM2*.

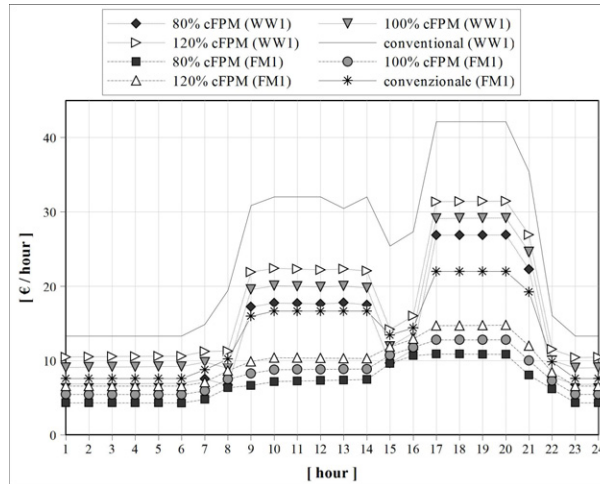


Figure 7: Sporting center: hourly cost for the trigenerative and conventional plants when varying the cost of the fuel to the prime mover, typical days *WW1* e *FM1*.

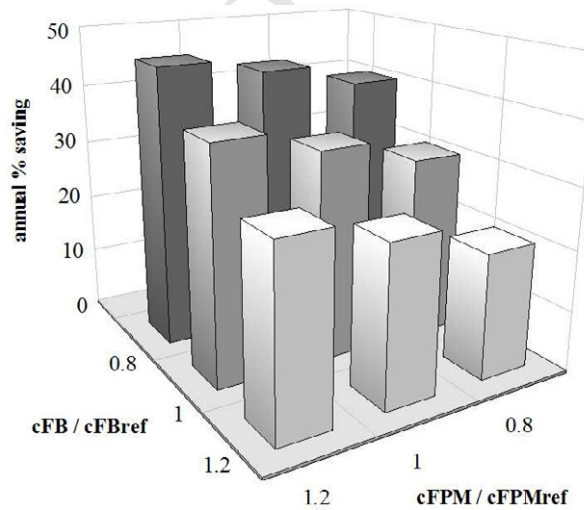


Figure 8: Sporting center: annual % saving using the trigenerative plant when varying independently the costs of the fuel to the prime mover or/and to the boiler.

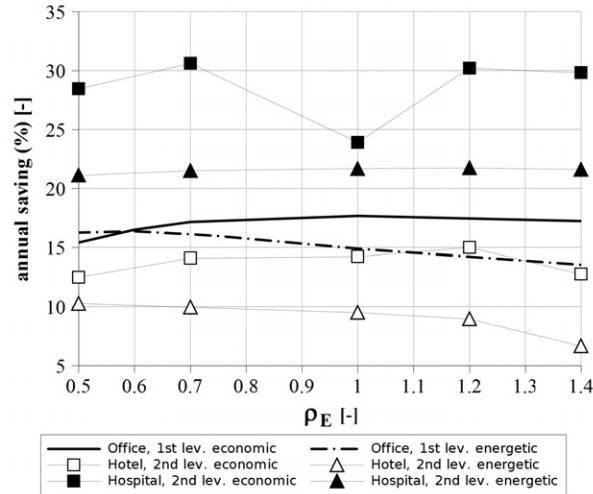


Figure 9: Annual % saving using the trigenerative plant varying the ratio between the maximum end user electric demand and the prime mover rated power, from both the energetic and economic points of view.

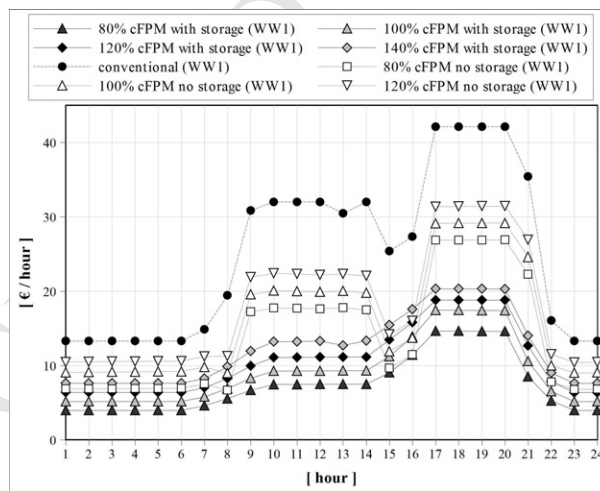


Figure 10: Sporting center: hourly cost (typical day WW1) for the conventional, trigenerative without storage systems and trigenerative with storage systems plants. The varying parameter is the cost of the fuel supplying the prime mover.