Methods for optimized design and management of CHP systems for district heating networks (DHN)

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Abstract

The paper analyzes some of the problems connected with the design, construction and management of cogeneration plants for district heating networks (CHP-DHN). Although the advantages of cogeneration systems compared with conventional ones for separate energy production, one of the unresolved problems is that of the variability of operating conditions, can often render the application of these solutions ineffective. In particular, the aim of this study is to propose a multi-objective optimization methodology that tries to take into account both energy and economic aspects.

After an analysis of the current scenario, the application and use of CHP plants in the international context and the main technological features, followed by the identification of incentive systems that have allowed or limited the spread, attempts are made to define a design methodology based on a multi-level optimum design based approach for increasing the operation share of CHP. The methodology starts from a general system vision, up to detailed aspects such as the management of a CHP-DHN system, taking into account the multiplicity of variables and constraints involved. This methodology has been applied to two case studies representative of the different applications, to verify its robustness and analyze the possible results obtainable.

In particular, a general case was taken into consideration, in which a first level design was performed by analyzing various possible system configurations and evaluating their goodness through the tools provided by the aforementioned multi-objective methodology. Then the methodology has been applied to an intermediate level, taking into consideration an existing CHP-DHN plant and going to evaluate the performance considering possible modification of the operation.

The results obtained confirm that a combined energetic and economic approach to design allows to obtain an economically feasible system, but at the same time avoids incurring over-sizing, under-sizing or functioning phenomena far from the concept of energy efficiency, difference of what happens for many plants today in operation. Furthermore, through a simple variation of the modularity of the plant, significant benefits can be obtained.

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Nomenclature

c	specific cost [€/kWh];
C	total cost value [€];
f	gain function [€];
F	dimensionless function;
G	gain from the sale of energy [€];
I	exergy losses [W];
p	price [€/kWh];
P	power [W];
Q	thermal energy required for the operation [kWh];
$\dot{Q}$	thermal power [W];
r_p	relationship between prices of electricity and thermal energy;
t_{eq}	equivalent time [h];
w	weight factor;
$\dot{W}$	electrical power [W]

Greek symbols

α_{CHP}	cogeneration share;
λ	cogeneration ratio;
η	efficiency

Pedices, acronyms and abbreviations

biom	obtained using biomass as input fuel
boiler	of the boiler
CHP	Combined Heat and Power or of the cogeneration system
cn	cumulative normalized
DHN	District Heating Network
el	of the electricity
h	instantaneous value
grid	from the grid
GT	Gas Turbine
i	relative to the single user
I	relative to the irreversibilities (exergy losses)

76	ins	relative to the installation
77	load	of the whole thermal load
78	O&M	relative to operation and management
79	ref	reference value
80	ST	steam turbine
81	th	of the thermal energy
82	tot	total value

1. Introduction

The combined production of electricity and heat (Combined Heat and Power, CHP) allows, in principle, to improve the overall energy efficiency of complex energy systems compared to the case of separate electricity production in thermoelectric plants and heat in conventional systems [1].

A district heating network (DHN) is a heat supply system based on centralized production or localized in a few production units and on distribution to the end user through an energy vector consisting of a fluid in temperature. with further savings prerogatives [2]. The idea of combining cogeneration systems with district heating (CHP-DHN) arises from combining the advantages of the two technologies, which can be reconciled in a natural way, to obtain a more efficient energy system, with a total cost reduction and an improvement in terms of environmental impact.

Anyway the problem is that thermal civil/residential loads are often difficult to be predicted because they are characterized by a strong seasonal and daily variability, also due to the different use of buildings; moreover, the thermal demand sometimes presents high ratios between maximum and minimum values (peaks of 3-10 times the base load). This does not allow the plants to be used in conditions close to those of the project, imposing the mandatory use of thermal integration systems, like auxiliary boilers, with the specific function of covering the peaks of the thermal load [3].

To date the design of CHP plants for district heating (CHP-DHN) is performed according to various methods, linked to technological needs, to economic incentive systems taking into account the characteristics of the loads to be satisfied. The choice of the management logic of these systems is one of the aspects that often constrain the sizing, producing, for similar applications, different engineering solutions [4].

In recent years, the diffusion of CHP plants has been strongly encouraged by the various national governments, especially in Europe [5]. The incentive system has often been linked to generic technical concepts such as "high performance" and "primary energy savings", by qualifying the plants through the use of synthetic indicators, the evaluation of which is often carried out in a particular condition. The use of these indicators, being connected to the design conditions does not evaluate the real operation of the plant. The economic advantage that derives from incentives tends therefore to overshadow some negative aspects related to the real operation of the systems [6]. In particular, observing the various CHP applications, there is a tendency to phenomena such as over-sizing or under-sizing, which cause distortions in the energy saving potential of those systems [7].

After carefully analyzing the problems related to the design and operation of the plants, the paper tries to develop an optimized multi-level design methodology, starting from a general analysis up to dealing with aspects of detail, and multi-objective , as it proposes a combined energy and economic analysis [8] assigning a penalty cost to the energy degradation: the aim is to maximize the share of cogeneration production by minimizing the contribution of additional thermal units (auxiliary boilers) thus reducing the irreversibility of the system. Then the methodology is applied to two case studies, one considering the design of a new plant starting from a typical load conditions, while the second is an optimization of the operation management of an existing plant considering the possible introduction of a storage system.

2. Cogeneration plants and district heating: technology, state of the art and open problems

The first element to be considered in the analysis of a CHP plants is the reference technology. Although often this is considered almost as a predetermined variable, this being mainly linked to the size, there are some peculiarities that make the various solutions quite different. A very important element is the parameter known as a cogeneration ratio λ, defined as the ratio between thermal and electrical power produced by the plant in nominal conditions:

$$\lambda = \frac{\dot{Q}}{\dot{W}} \tag{1}$$

	Technology	λ values	Positive characteristics	Negative characteristics
Medium to high size	Steam turbine (ST)	0.5÷10	Modulability, quite low costs	Quite low electrical efficiency, not good for intermittent operations
	Gas turbine (GT)	0.5÷2.5	High temperature recovery, high flexibility	Low operational flexibility, medim to low efficiency values
	Combined cycle (CC)	0.5÷3	High electric efficiency, possibility of modulation	Reduced starts-and-stops, high specific costs
Medium to low size	Internal combustion engines (ICE)	1÷5	Flexibility, quite good efficiency at partial load	Direct link between electricity and thermal energy
	ORC plants (ORC)	0.5÷10	Adaptability at Renewable Energy Sources	Use of a different operating fluid
	Fuel cells (FC)	0.5÷2	Very low power	Technology not commercially developed
	Microturbines (μTG)	0.5÷2.5	High quality technology	Reduced flexibility, quite low efficiency values, high costs

Table 1: cogeneration technologies and main features.

the main CHP technologies currently available are shown in Table 1. A primary distribution system and a secondary one are required, deriving from the main line of distribution a network of pipes with reduced diameters and operating pressures. The network hosts secondary heat exchange substations and pumping substations. The exchange substations allow transferring heat for the final uses.

Fig. 1 shows a typical scheme of a district heating network with the various components (CHP units, auxiliary boilers, heat exchangers, storage systems and piping network); the typical values of the main operating parameters are shown in Table 2.

The international scenario of development and diffusion of cogeneration systems is quite variable from country to country, but in general the role that the incentive systems introduced in each country play, has been important. These tools have often led to a development linked to purely economic reasons to replace the original energy objectives [9]. Some countries have obtained important benefits from a more effective and structured incentive system (e.g. Denmark and South Korea). Alongside incentives, other factors that have diversified the spread of these systems are the typical climate, population and geographical extent. Table 3, constructed referring to the data from Euroheat & Power 2015, shows what is the current state of diffusion of CHP-DHN systems in the Italian case and in the two virtuous countries mentioned.

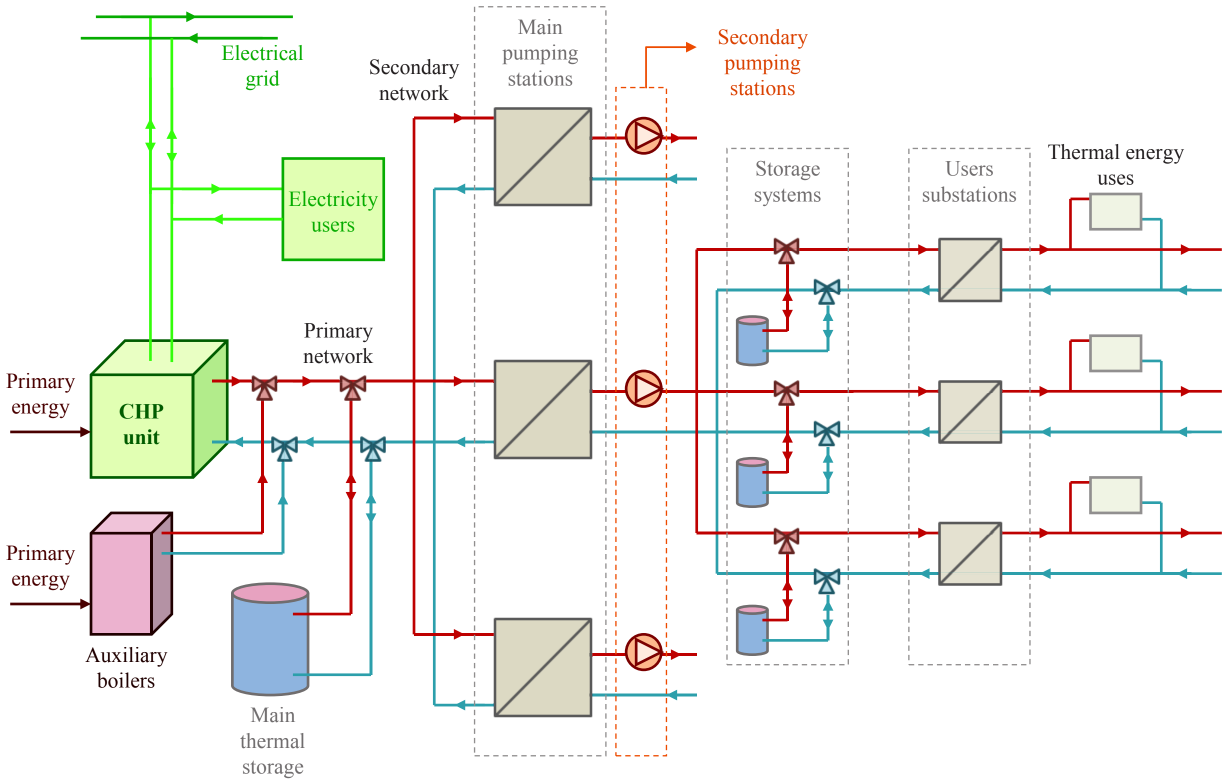


Fig. 1. General scheme of a district heating network.

The difficulties related to design, combined with the distortion of the objectives often generated by the incentives, have determined a series of problems still open, first of all the already mentioned over sizing of the CHP units resulting in poor efficiency in operation outside the nominal conditions and the frequent use of supplementary thermal units with CHP systems used to cover only the basic heat load values. It is therefore necessary to identify suitable methods to redirect the development and implementation of these systems in the energy optics. To obtain results from a method such as the one described, however, it is necessary the knowledge of loads.

Network	**Fluid velocity**	**Max pressure**	**Input Temperature**	**Return temperature**
Primary	2÷3.5 m/s	10 bar	90 °C	70 °C
Secondary	1÷2.5 m/s	6 bar	80÷85 °C	60÷65 °C
Substations	**Thermal power**	**Input Temperature**	**Return temperature**	
Primary	250÷2000 kW	80÷85 °C	60÷65 °C	
Users	15÷200 kW	70 °C	50÷55 °C	

Table 2. Main features of the district heating networks: primary heat exchangers and substations.

	Denmark	**South Korea**	**Italy**
CHP power installed (GW)	6.0 GW	7.7 GW	27.0 GW
CHP vs. electricity production	66%	5%	48%
CHP for DH production	73%	67%	68%
Thermal energy for DH (GWh)	29323 GWh	47859 GWh	9200 GWh
Poputation (Millions)	5.64	50.42	60.80
Population served by DH (%)	63%	15%	6%
Incentivation policies	Carbon taxes; feed-in tariffs; fiscal incentivations	Subsides	White certificates; incentivations
Climatic characteristics	Cold; quite homogeneous in the territory	Climate; reduced disomogeneity	Variable and not homogeneous

Table 3. Comparison of the spread of cogeneration and district heating in three different countries

3. Definition of electrical and thermal loads for CHP design

The most important problem connected with the design of CHP systems is the variability of loads in the different operating conditions, both during the single days and in the different seasonal conditions. This difference is particularly relevant for what concerns the thermal load.

A first topic that need to be carefully analyzed when one thinks about the design of a CHP plant for a DHN is the definition of thermal and electrical loads. Both the electrical and thermal load show a seasonal and a daily variability, in comparison with the trend of the outside temperature and considering the various hours of the day. In a lot of application of civil structures, the differences between working days and holidays of daily loads must be taken into account. Fig. 2 shows the particular trend of thermal and electrical load for some University buildings, during the different months of the year and during the different hours of the day, with reference to the particular day.

Fig. 2, obtained from [10] provides the experimentally obtained value of electrical and thermal loads for a typical working day during winter and summer time and typical weekend day during winter and summer time, obtained in two Italian University buildings. The data are obtained by means of direct measurements.

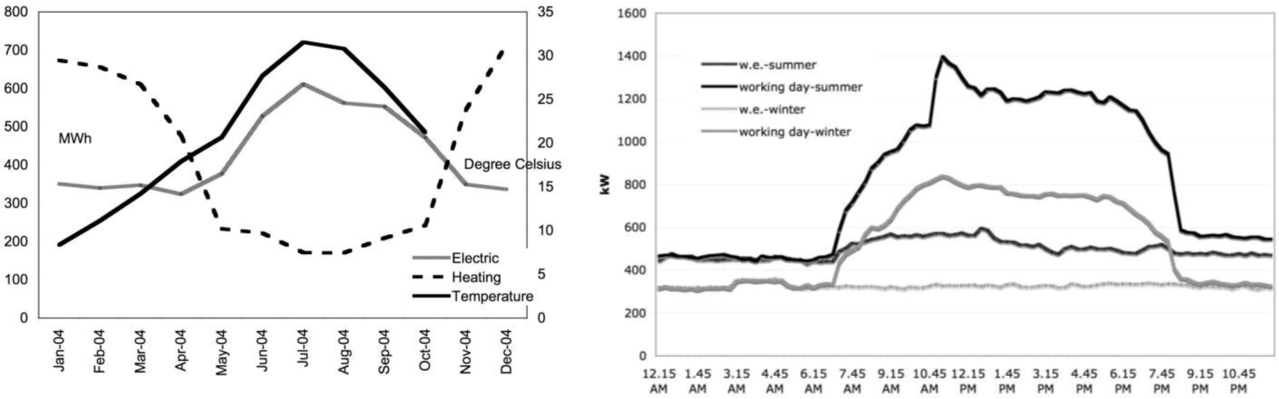


Fig. 2. Variability of electrical and thermal loads (data for the University of Siena Science Building according to the data of [10]).

Given the importance of the loads and in light of the strong variability associated with them, an analysis of some typical cases has been performed. Attention has been focused on the aggregation of the data in groups of utilities and buildings. This can be considered as a mean for a preliminary homogenization of the loads in view of the realization of a CHP plant, proposing a general method for quantifying the advantages obtainable from the use of this tool. In particular, an analysis was carried out on four different uses: residential, offices, hospital and university.

In the case of a single user it can be quite simple to obtain the typical load profile by means of direct measurements. The problem is more complex in case of a generic users before the installation of the plants: in this case a profile of the user has to be identified using typical load profiles.

Typical curves defining electrical and thermal loads have been constructed in the form of "normalized cumulative" curve, obtained by calculating the cumulative instantaneous values as the sum of the values of the various individual users divided for the maximum of the sum of the instantaneous values of the same:

$$P_{h,cn} = \frac{\sum_i^n P_{h,i}}{max\{\sum_i^n P_{h,i}\}} \qquad (2)$$

Where P is the generic power, the subscript h indicates the instantaneous value and the subscript cn stands for cumulative normalized. Considering the right side of the equation, index i of the sum indicates the different type of users (assuming to assign a progressive number to the four available) and n is the total number of cumulative users (which will vary between 2 and 4 for the various combinations). The users are grouped considering different typologies (residential user, various civil users like hospitals, university buildings, offices and industrial users) and for each group of users the graphic shows a value of the normalized power ranging between 0 and 1. Obviously, to obtain a dimensional value it is necessary to multiply the value reported in the graphs and the total power installed to serve the different users: the value can be quite different.

This procedure allows obtaining benefits in terms of homogenization of the energy demand, through reduction of peaks in the corresponding graph, benefits that become exploitable from the point of view of a better sizing of the plants and their more efficient operation. Fig. 3 shows for example the diagrams relative to the electric loads in all the analyzed combinations of typical buildings use compared to the various loads. The dimensionless value reported in the ordinate axis represents the ratio between the power required and the maximum power required during the day. A similar behaviour could be found for the thermal loads.

The aggregation of data is a preliminary operation before the design: if there is the possibility to choose the utilities to be fed with a cogeneration plant and in particular the load trends are available from measurements or different forecasting methodologies, the application of the method introduced in this paragraph allows taking a step forward in the design. The choice of an overall load having a performance with functional characteristics for a more correct operation of the plant constitutes an advantage and creates conditions that favour, in addition to operating management, the definition of an optimal size of the plant. This can be interesting before the preliminary design of a CHP-DHN system even if it is quite difficult to verify this kind of opportunity in the practical experience.

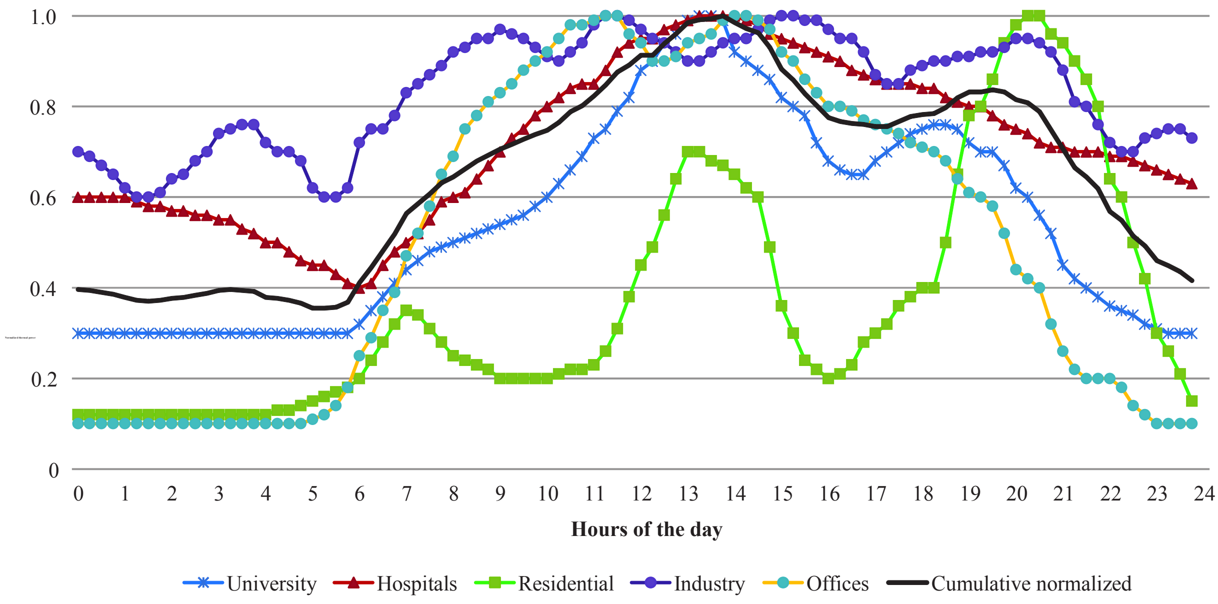


Fig. 3. Normalized electrical power for different aggregation of energy “users” in Italy

4. Methodologies for optimized design and management of CHP for DHN network

The design of cogeneration systems is often based on satisfying a specific thermal load, usually low, by assigning to auxiliary units and storage systems the task of regulating and modulating the system. This tends to reduce the percentage of operation in cogeneration defined as the ratio of thermal energy from CHP, Q_{CHP} and the total thermal energy required Q_{load}:

$$\alpha_{CHP} = \frac{Q_{CHP}}{Q_{load}} \tag{3}$$

Several attempts are available in the literature to provide design methods that are qualitatively better than those commonly used today based mainly on economic elements, in the field of CHP systems: some more or less homogeneous groups can be identified, reported in Table 4.

Despite the apparent wide availability of methodologies for the optimized design of CHP systems, many of those analyzed correlate with particular application situations and plant types: each author investigates some relevant aspects associated with cogeneration systems, trying to propose optimizations of the system components or specific design criteria related to certain contexts.

Approach	Characteristics and main objectives	References
Design	Search for the best plant configuration combined with an optimal distribution system and an interconnection between functional utilities and design objectives	[11-14],
Operation and management	Determination of the operational management to be adopted, in particular by using the instrument constituted by the thermal storage	[15-17]
Performance	Design of self-sufficient CHP systems with minimum energy excesses; search for methods and indicators to correctly evaluate the achievement of the objectives	[7], [18-19]

Table 4: Studies available in the literature on the topic of the optimized design of CHP-DHN systems.

However, two open issues can be identified. The first is the extremely high non-uniformity, which presents very general cases together with particular problems, not allowing information to be obtained in situations that go beyond those proposed. The second concerns the lack of a general vision that allows to characterize the problem related to the design of CHP-DHN systems in a valid way for any application, and not bound to the individual case, so as to be able to identify solutions that can be readjusted to different situations.

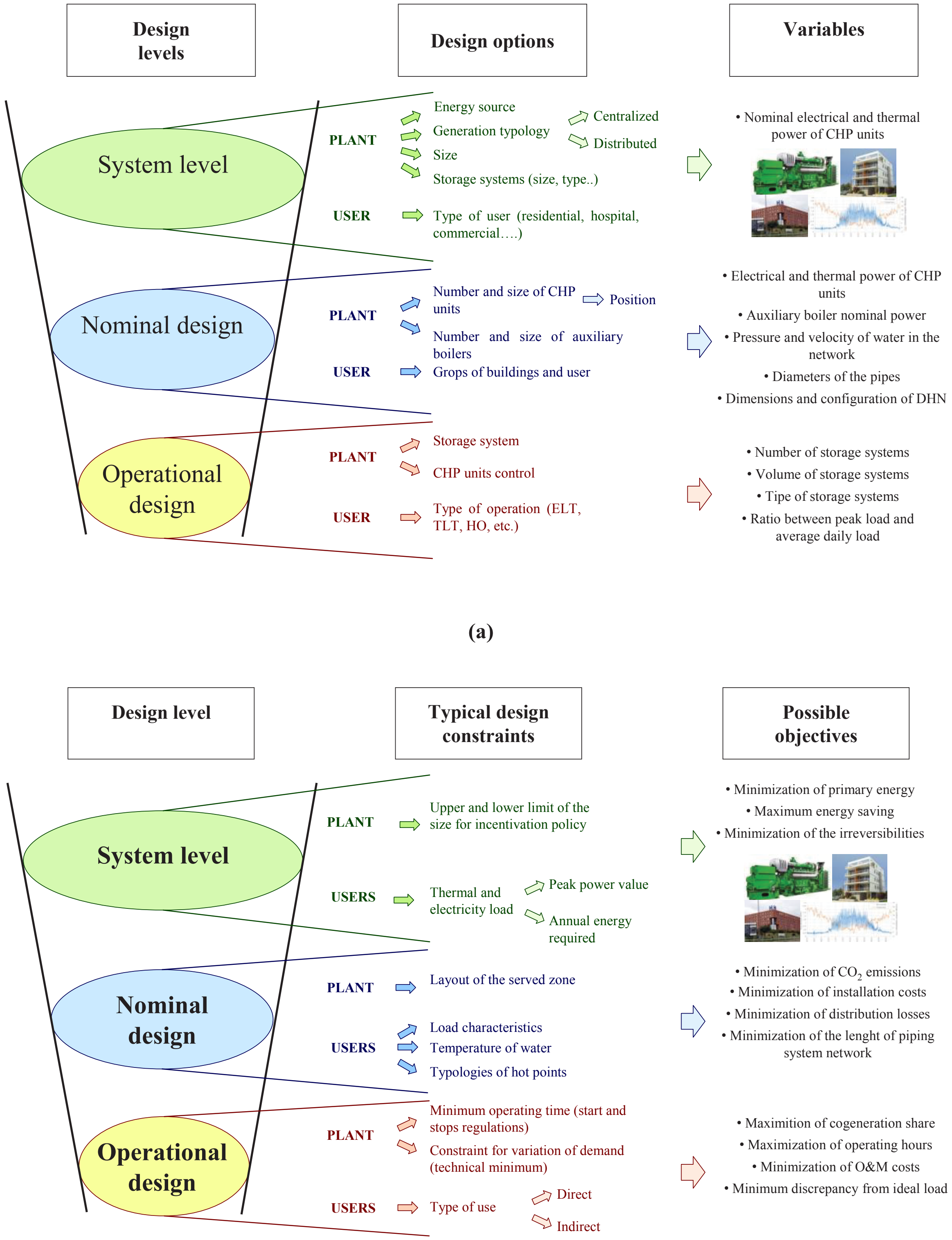
What is needed is the union of all the approaches under a single design method of CHP-DHN systems: the interest should pass from a detailed vision to a general one, involving all the positive aspects emerging from the available studies to enclose them under a common methodology of analysis. The idea is to start from a broader vision, at a system level and to develop design step by step, with the aim of identifying at first the not optimal solutions to be discarded at an initial step, and proceed to investigate at a level of detail only those that are valid from an energy point of view. A relevant example is given by over sizing of the thermal integration units (auxiliary boilers): a cogeneration plant for district heating that works at full capacity throughout the year will certainly operate for a high number of hours and will achieve the objectives related to the return on investment in a short time. However, a plant of this type will certainly require an additional thermal input from one or more auxiliary thermal devices, and therefore from the point of view of the exergy efficiency it will not be optimal at all. Following the analysis of the literature and the problems identified, therefore, this work proposes a method that allows facing in general the design of CHP-DHN plants and to develop it with a multi-objective approach through a declination of the multi-level design approach thus structured:

- system design;
- nominal design;
- operational design.

The optimized design consists in the definition of a problem in which there are some objective functions and some boundary conditions that constitute the constraints. This concept is important because it is the one that creates the fundamental distinction between designs aimed only at compliance with specifications and optimized design: in the first the constraints are precisely the design specifications, while in the second are also some conditions that guide the problem towards optimal solutions. It is therefore possible to identify a structure that underlies the optimized design:

- model of the physical system;
- definition of the variables;
- determination of the objective functions;
- identification of the constraints.

Fig. 4 introduces the logic on which the optimized design methodology proposed in this work is developed. The methodology is articulated at three different levels identifying, for each of them, the main aspects related to the system under analysis (in this case a CHP-DHN) and to the users of the district heating. In Fig 4(a) some possible design options and possible variables are described, while in Fig 4(b) possible objective functions and design constraints for the different levels are defined. The analysis starts from the identification of the constraints and of the possible objectives to be achieved for the optimum design. The problem is then to finally determine the values assumed by the variables involved. The process is iterative: by acting on boundary conditions, objectives and design variables, it is possible the determination of the optimal values for the variables that describe the analyzed system.



(a)

(b)

Fig. 4: three-level scheme proposed for the development of the design of cogeneration systems for DHN: (a) variables and parameters at the three levels; (b) typical objectives and design constraints

4.1. Multi-objective optimization methodology for the design of CHP-DHN systems

The optimization methodology proposed in this work is based on the idea of assigning a penalty cost to the irreversibility. The main idea is that in the economic analysis of the CHP-DHN system the energy degradation connected to the operation of both CHP units and supplementary boilers assumes an economic value and therefore constitutes a cost item.

The minimization of the indicator so defined permits of defining a kind of multi-objective optimization in which economic and energetic elements are considered.

To implement such a methodology, a first analysis of the costs attributable to a CHP-DHN plant was performed, identifying three main items: installation costs, C_{ins}, operating and maintenance costs, $C_{O\&M}$ and the cost of the resource used, C_{res}. To them it is added the cost assigned to the irreversibility of the system, indicated with C_I. The total cost function, defined as the sum of all costs, is given by:

$$C_{tot} = C_{ins} + C_{O\&M} + C_{res} + C_I \tag{4}$$

The objective function for the optimization is a gain function f_g defined as:

$$f_g = \left(p_{el}\dot{W} + p_{th}\dot{Q}\right) \cdot t_{eq} - C_{tot} = f - C_{tot} > 0 \tag{5}$$

Where f_g is defined as the gain factor; f is the gross gain function; and p_{el} and p_{th} the selling prices of electricity and heat given in €/kWh; t_{eq} is the equivalent annual operating time, expressed in hours. The most important element of the methodology is the definition of an appropriate value of the cost of irreversibility (exergy losses), c_I.

Assuming to assign to a system that produces only electrical energy a cost of irreversibility proportional to the value of the price of electricity and thermal energy; equal to $p_{el}\eta_{el,ref}$, and to one for thermal energy production only, a cost $p_{th}\eta_{th,ref}$, for a CHP system it is possible to think to a structure of the type:

$$c_I = \frac{w_{el} \cdot p_{el} \cdot \eta_{el,ref} + w_{th} \cdot p_{th} \cdot \eta_{th,ref}}{w_{el} + w_{th}} \tag{6}$$

where $\eta_{el,ref}$ and $\eta_{th,ref}$ are reference values that can be identified considering the current technological level, while weight factors are w_{el} and w_{th} respectively. Considering a typical situation, the values of the references efficiency values for $\eta_{el,ref}$ and $\eta_{th,ref}$ can be for example 0.4

and 0.85, while the weight factors can be chosen arbitrarily. In general cases, the expression of the cost of the irreversibility becomes:

$$c_I = \frac{\eta_{el,ref} + \eta_{th,ref} \cdot \frac{\lambda}{r_p}}{\lambda + 1} \cdot p_{el} \tag{7}$$

where λ is the ratio of cogeneration and $r_p = p_{el}/p_{th}$ is the relationship between prices of electricity and thermal energy. The value can be obtained as a ratio between the actual cost of electricity and the cost of natural gas: it can be considered typically in the range between 2 and 4.

The expression thus obtained makes use of only dimensionless parameters, with the exception of p_{el}, which is assumed in this treatise as the main economic reference parameter. It is possible to formulate the problem of multi-objective optimization by using the utility function method [20], which envisages defining a function given by the sum of the individual objective functions, each multiplied by a weight. The optimization problem will therefore consist in finding the vector of variables

$$\boldsymbol{X} = \{x_1, x_2, \dots, x_n\}$$

for which it is possible to minimize the utility function defined by the total cost of the system:

$$U = C_{tot}(\boldsymbol{X})$$

subject to the constraints:

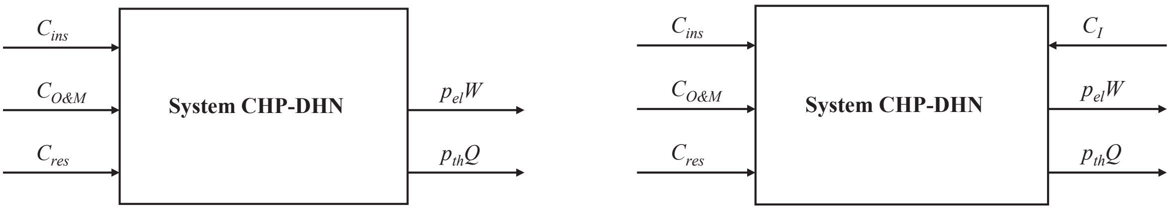
$$g_j(\boldsymbol{X}) \leq 0, \qquad j = 1,2, \dots, m$$

being the constraints defined by the appropriate boundary conditions identified in the design. The operational cost of the plant will be expressed in €/year, considering an economic life time of the plant, which allows an objective comparison of different configurations.

The situation is represented in Fig. 5 in which the difference between the classical economic analysis and the proposed analysis is evidenced.

The basic idea of the method is the following: considering a typical CHP plant with an auxiliary boiler for the thermal integration from a qualitative point of view the classic economic approach, represented in Fig. 5(a) determines a reduction of the size of the CHP plant and a relevant use of the auxiliary boiler, that has a low economic cost and a quite high First Law efficiency even if very low Second Law efficiency and quite high irreversibility. This is not good in general because does not permit to really appreciate the beneficial effect of CHP plants that are often designed on the base of a minimum thermal load. An approach like the one proposed in the paper and represented schematically in Fig. 5(b) by means of an introduction of a penalty to the irreversibility (represented by the cost c_I will surely determine an increase of the size of the CHP and a reduction of the size and of the operating time of the auxiliary boiler.

The method exposed in Fig. 5(b), that can be considered similar to a “thermoeconomic” based approach, has been already applied by one of the author of the present paper, to the context of different energy systems, like exposed in [21].



(a) (b)

Fig. 5: Scheme of costs and gains associated with a CHP-DHN system:
a) in a traditional economic analysis; b) in a combined energy and economic analysis.

It was considered appropriate to define another expression of the cost of irreversibility that is based on that already obtained and that adequately penalizes the degradation connected to the thermal integration units. By assimilating a boiler to a cogeneration unit in which the installed electric power is set at zero, it is possible to obtain an expression for the costs of the irreversibility due to the operation of the auxiliary boiler:

$$c_{I,boiler} = f_{c,b} \cdot \frac{\eta_{th,ref}}{r_p} \cdot p_{el} \tag{8}$$

where $f_{c,b}$ is a corrective factor chosen appropriately in such a way as to guarantee compliance with the condition $c_{I,boiler} > c_I$, in order to avoid that optimization leads to an unbalanced system in favour of production from auxiliary units determined by lower relative cost of the irreversibility of this last component. Similarly, it is possible to state that the method adequately penalizes the solutions that make extensive use of electricity taken from the national network, to avoid a strong underproduction aimed at transferring costs to the end user. To do this, a cost of irreversibility has been introduced. It is associated with the electric energy withdrawn, a function of the average national electrical efficiency:

$$C_{I,el} = c_{I,el} \cdot I_{el} = c_{I,el} \cdot \frac{1-\eta_{el,ref}}{\eta_{el,ref}} \cdot W_{grid} = c^{*}_{I,el} \cdot W_{grid} \tag{9}$$

where W_{grid} is the electricity from the grid, I_{el} the energy degradation associated with it and $c^{*}_{I,el}$ represents a specific cost of the irreversibility according to the average national generation efficiency, dependent on the specific cost, $c_{I,el}$ which can be identified as the price of electricity, p_{el} An allocation of costs to the irreversibility thus articulated guarantees:

- the penalization of operational mode characterized by greater irreversibility;
- a more significant penalization of the irreversibility deriving from the use of thermal integration units compared to that associated with the degradation in the CHP;
- a penalty associated with electricity taken from the grid, which avoids solutions characterized by a low percentage of cogeneration share.

In particular, the method proposed allows to identify an optimum that has the following characteristics:

- from an electrical point of view, production is as close as possible to that required;
- from a thermal point of view, production from auxiliary units is reduced to a minimum and is the one that minimizes the energy degradation associated with the energy produced in cogeneration.

The cost of the overall irreversibility will therefore be given by:

$$C_{I,tot} = C_I + C_{I,boiler} + C_{I,el} = p_{el} \cdot \left(\frac{\eta_{el,ref} + \eta_{th,ref} \cdot \frac{\lambda}{r_p}}{\lambda+1} \cdot I_{CHP} + f_{c,b} \cdot \frac{\eta_{th,ref}}{r_p} \cdot I_{boiler} + \frac{1-\eta_{el,ref}}{\eta_{el,ref}} \cdot W_{grid} \right) \tag{10}$$

It should be observed that, for a qualitative analysis, in which only a first assessment of costs has been made, the condition $f_g = f - C_{tot} \geq 0$ may not be verified. In this case, it would be advisable to make a comparison referring to the gross profit/cost ratio, of the dimensionless type, capable of providing an effective comparison criterion independent of this aspect. This function is the ratio between the gross gain function f and the total cost:

$$F = \frac{f}{C_{tot}} \tag{11}$$

The F function can be used both as objective function to be maximized and as multi-objective indicator for a comparative analysis of different solutions.

5. Examples of application of the methodology developed to case studies

The developed methodology has been applied to two different case studies in order to understand the modification that can be obtained with respect to conventional design. These two different applications make it possible to investigate the effectiveness of the two-design methodologies described in Fig. 4. In the first case the optimum design is carried out at the upper level: “system level”. The optimal configuration to be implemented is investigated as a function of an electrical load and two different thermal loads. This makes it possible to address the issue of the choice of the optimal plant configuration of a hypothetical plant able to satisfy a given load. The second case moves the analysis to a “nominal design level”: the limits of the operation adopted in an existing plant are discussed, proposing solutions for the modulation according to the thermal load.

5.1. First case study: analysis at the system level applied to the design of a medium to high size new plant

The plant under analysis is a typical CHP plant in which electricity and thermal load can be previously defined. Concerning the thermal load, two users are present: a first identifiable as a district heating network, with associated thermal demand at medium to low temperature (water at 90 °C), and an industrial user, characterized by a thermal demand in the form of medium and high pressure steam and by electric power requirements. Knowing the various electrical and thermal load assumed over a reference period corresponding to about one year as represented in Fig. 6, the problem of design has been studied from the point of view of determining the number and type of cogeneration units and the auxiliary boiler. In the actual configuration the plant is based on a CHP unit with a GT system for electricity production with a heat recovery system and an auxiliary boiler for the production of thermal energy surplus. In a considerable part of the operating time, the auxiliary boiler is in operation and this component is responsible for a great amount of exergy losses.

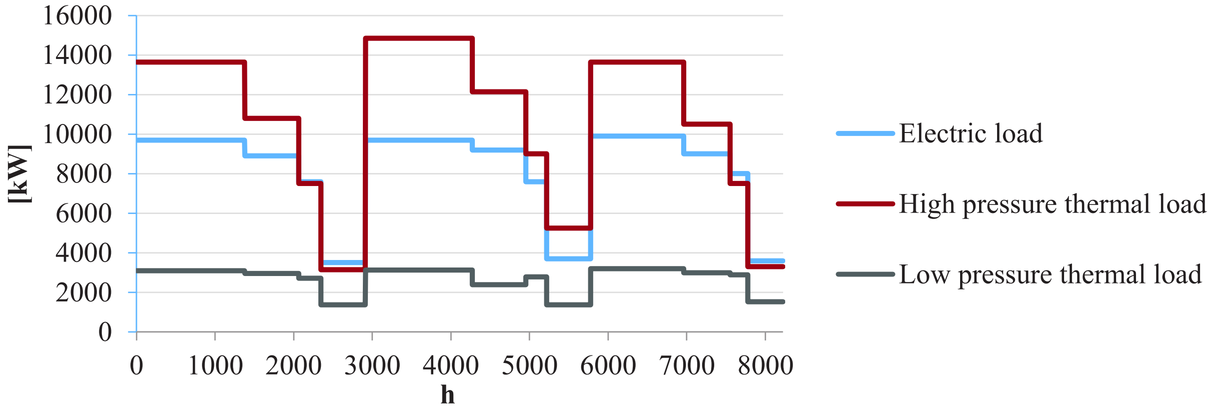


Fig. 6. Thermal and electrical load trend during the operating time of approximately one year

The objective of the optimum design process based on the application of the optimum design procedure described in section 4.1 is the maximization of the operating share of CHP. In this perspective it can be possible to consider the possible elimination or the reduction of the size and of the operating time of the auxiliary boiler. The following step of the optimum design procedure consists in selecting the available technologies that can be used, fall on gas turbine (GT) and steam turbine (ST), and then identifying the machines, available on the market, of a size suitable for a quantitative assessment.

As described in Fig. 6, the maximum electrical and thermal load required are about 10000 kW and 15000 kW respectively: so this can be considered a medium to high plant. Four types of system configurations have been analyzed: single GT, double GT, single ST, double ST (for a total of 20 different configurations).

Fig. 7 shows the trend of the total costs (represented by the istograms) and of the function F, represented by the black line, for the different configurations analyzed. It appears clearly that the best configuration is the one that minimize the total cost and/or maximize the function F: in the case under analysis is the configuration with two gas turbines of different size: SGT200 + GPB17D). Fig. 8a shows the trend of the electric power produced compared to the electric load, while Fig.8b shows the trend of the thermal power produced by the cogeneration units and by the auxiliary boiler compared to the thermal load (graphs relative to the optimal configuration with 2 GT: SGT200 + GPB17D).

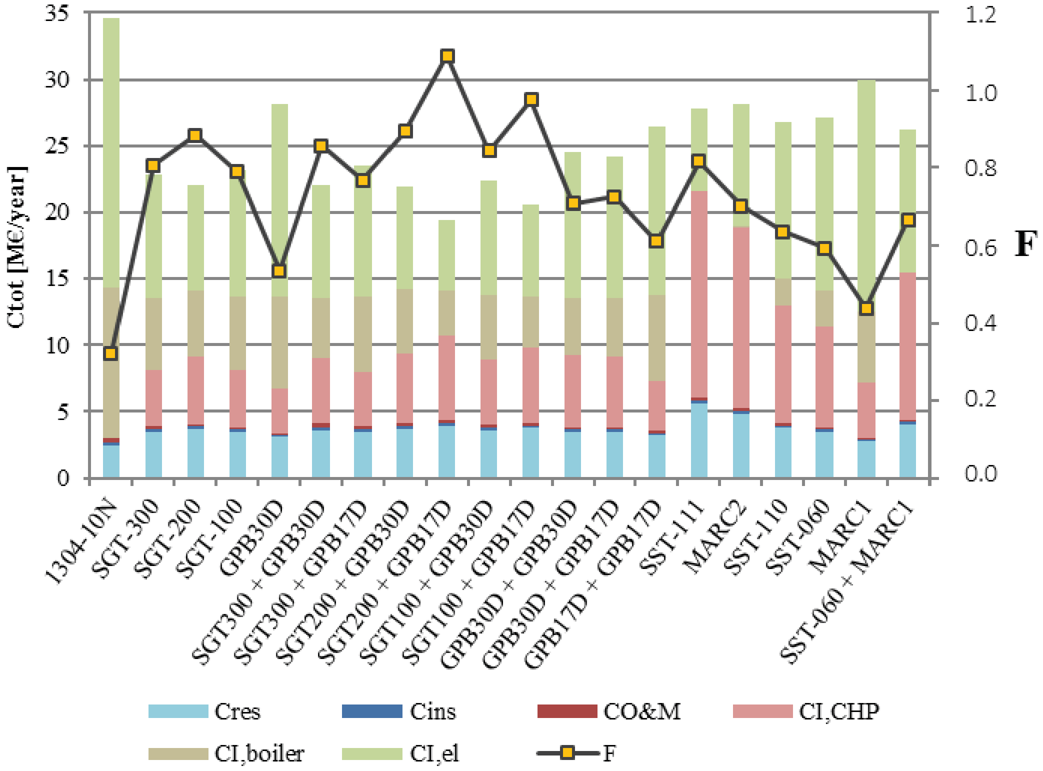
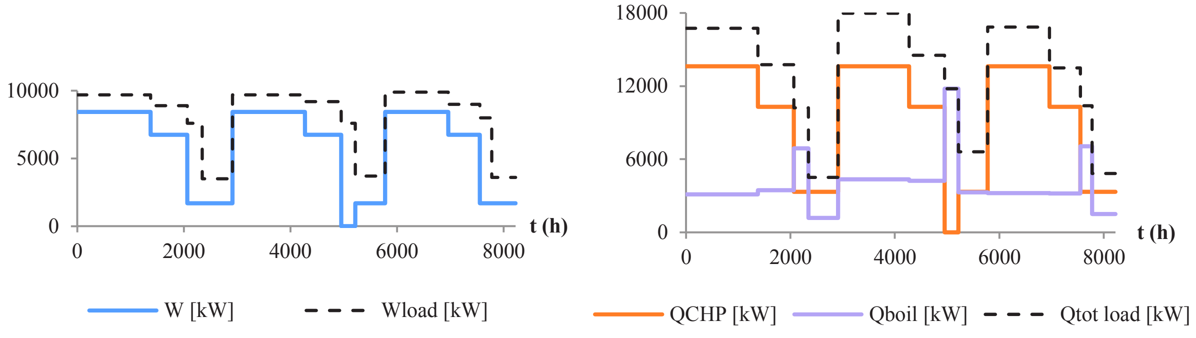


Fig. 7. Results obtained from the methodology applied to the first case study



(a) **(b)**

Fig. 8. Load conditions (dashed lines) and satisfaction with CHP and auxiliary boilers during the year

5.2. Second case study: analysis at intermediate level applied to an existing plant for the modification of the operational strategy

The second case study concerns an existing CHP plant located in the north area of Italy, powered by biomass and connected to a district heating network. The power plant is a typical CHP plant based on a solution of a steam turbine. Fig. 9 provides the trend of the thermal load during the whole year: it varies from approximately 700 kW during summer time up to 6000 kW (6 MW) during winter.

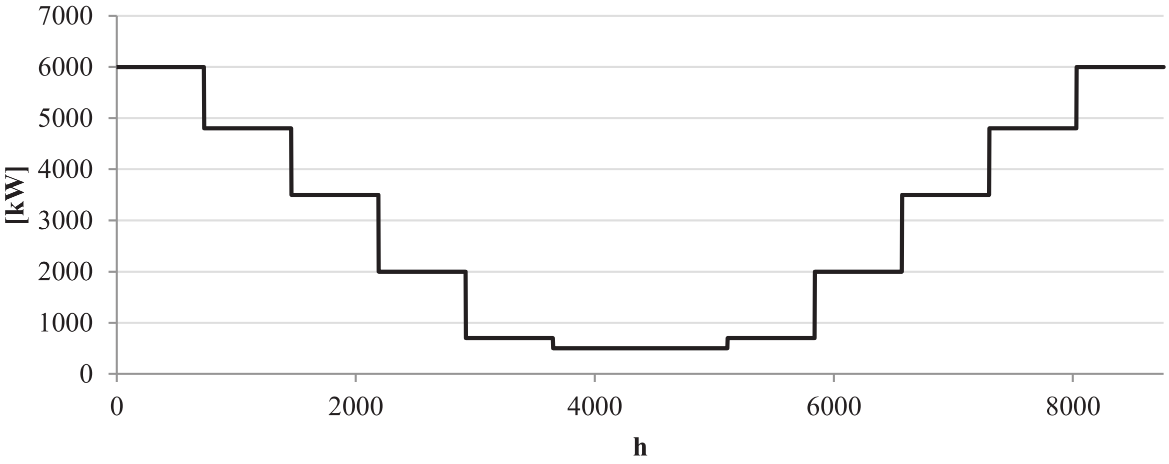


Fig. 9. Average monthly thermal load hypothesised for the duration of one year

In the actual configuration the cogeneration plant is characterized by a steam turbine consisting of a high pressure and a low pressure section. No auxiliary boiler is used due to the fact that the plant is designed to be oversized with respect to the maximum thermal load. The modulation, in this case, is allowed by acting on the flow rate tapped by the high pressure section, with the increase of which the thermal power available for district heating is increased and the evolving steam flow in the low pressure section is reduced, and with it electrical production. The total thermal power of the steam boiler is approximately 12.5 MW, while the maximum electrical production, obtained during summer time is about 2.9 MW.

Two operating conditions are available now: a winter time operation mode (6 MW for DHN and 1 MW of electricity production) and a summer time operation mode (0.8 MW for DHN and 2.9 MW of electricity production. The plant operates about 3000 hours in “summer mode” and the remaining 5800 hours in “winter mode”. The actual operation of the plant is characterized by a high amount of irreversibility (exergy losses).

Two variants have been proposed for the alternative modulation to the two-level operating logic adopted today (current status), which is based on a maximum thermal (winter) or maximum electric (summer) regime and minimum thermal power. The proposed variants introduce one (3 levels) or two (4 levels) intermediate operating modes acting on the steam flow rate tapped by the turbine and on the flows circulating in the heat exchanger.

The results show that, just introducing one or two additional operating models for the mid-season operation, it is possible to reduce the irreversibility up to 80% and increase the value assumed by the F function up to 15% in the best case analyzed with respect to the current operating mode; the methodology has therefore shown that a simple change in the operation of the plant can bring significant energy and economic advantages. Fig. 10 shows for example the variation of energy production and degradation considering the possible transition from the current state to a regulation based on three of four levels. It is remarkable to say that a regulation based on four levels rather than the current one based on only two permits a reduction of the energy degradation up to the 80% with respect to the actual level.

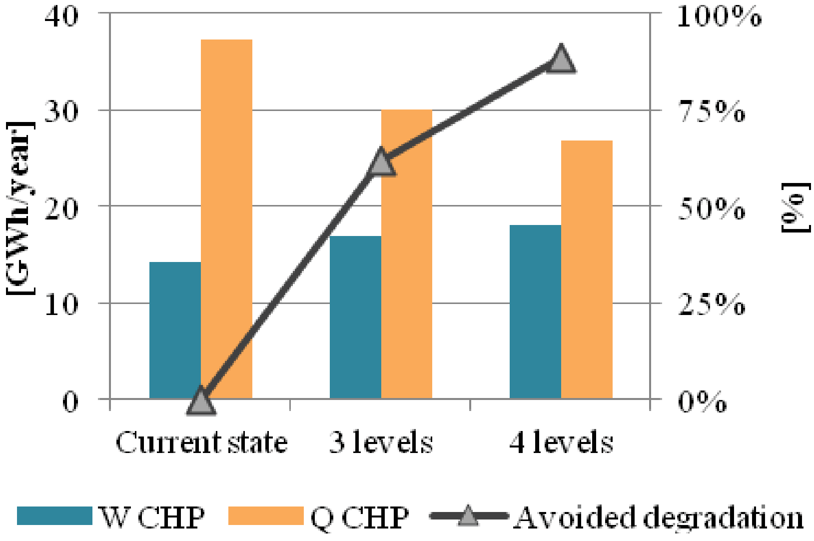


Fig. 10. Results obtained in terms of avoided energy degradation with respect to the current state with a possible regulation based on different regulation based on two or three levels load.

6. Conclusions

The present work has considered the problem of the design of CHP and in particular of CHP-DHN for the civil/residential field and has identified possible strategies for increasing the energy efficiency of the systems combining the perspectives of the Second Law of Thermodynamics of reducing the global irreversibility of the system and the general economic objective of minimizing the total operation costs.

After examining the studies available in the literature aimed at defining methods for the optimum design of these systems, an original method, based on a multi-level and multi-objective perspective has been outlined, discussed and analyzed.

The method proposes to approach the optimum design of the CHP-DHN system with a general perspective considering three possible levels of the system description, starting from top (general description) to bottom (more detailed description).

The optimum design, at all the levels, can be obtained using a cost function that minimize the operational cost of the system, including both economic and energetic elements. The real novelty of the methods stands not only in the definition of three levels of description of the system under analysis, but also in the definition of a specific objective function, including a term of penalization to the irreversibility caused by the operation of the plant.

The method can be used both for the optimized design of new plants, knowing the electrical and thermal load and for modifying existing plants with the modification of existing components (for example the reduction of size and operational time of auxiliary boilers) or with the introduction of some additional components (like storage systems) or otherwise just for the definition of the optimal operating strategy.

The method has been tested with reference to two specific cases and even if the analysis is limited to the two cases discussed, the results expected with the application of the proposed method can be summarized by the following points:

- it allows to analyse systems at a reduced level of complexity with come into play many variables that greatly complicate the analysis;
- compared to a conventional economic analysis, it includes in the cost function an item that take into account the irreversibility deriving from the operation of the system and consequently the increase of size and operational time of CHP with respect to auxiliary boilers;
- if applied to CHP systems, it can represent and effective method for achieving the goal of obtaining energy efficiency and improvement of economic analysis.

The central point is the attribution of a cost to energy degradation: the criterion used to determine the value of this parameter therefore plays a key role in the application of the methodology;

A further element that can be extrapolated considering the results of this work is the idea of a review of incentivation mechanisms for CHP systems: they could be formulated according to a multi-objective vision, resorting no longer to individual performance indicators, ineffective in describing a plant comprehensively, but trying to identify, on the basis of multiple objectives, a number and a typology of indicators such as to constitute, if properly combined, a good criterion for the valorisation of truly efficient solutions and for a correct allocation of economic supports.

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