Multi-objective optimization for the maximization of the operating share of cogeneration system in District Heating Network

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Abstract

The aim of the paper is to define optimal operational strategies for Combined Heat and Power plants connected to civil/residential District Heating Networks. The role of a reduced number of design variables, including a Thermal Energy Storage system and a hybrid operational strategy dependent on the storage level is considered.

The basic principle is to reach maximum efficiency of the system operation through the utilization of an optimal-sized Thermal Energy Storage. Objective functions of both energetic and combined energetic and economic can be considered. In particular, First and Second Law Efficiency, thermal losses of the storage, number of starts and stops of the combined heat and power unit are considered. Constraints are imposed to nullify the waste of heat and to operate the unit at its maximum efficiency for the highest possible number of consecutive operating hours, until the thermal tank cannot store more energy.

The methodology is applied to a detailed case study: a medium size district heating system, in an urban context in the northern Italy, powered by a combined heat and power plant supported by conventional auxiliary boilers. The issues involving this type of thermal loads are also widely investigated in the paper. An increase of Second Law Efficiency of the system of 26% (from 0.35 to 0.44) can be evidenced, while the First Law Efficiency shifts from about 0.74 to 0.84. The optimization strategy permits of combining the economic benefit of cogeneration with the idea of reducing the energy waste and exergy losses.

Keywords: Combined Heat and Power, District heating systems, Thermal Energy Storage, Optimization

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Nomenclature

C	cost of the storage tank [€]
C_{cm}	specific cost of the storage tank [€]
C_r	reference cost [€]
E	energy [kWh]
f_i^{max}	maximum value for the *i*-th performance parameter
f_i^{min}	minimum value for the *i*-th performance parameter
F_i	constant factor of the composite indicator for the *i*-th performance parameter
h	hours [h]
I	composite indicator
N	number of operation hours
T	temperature [°C]
U	heat transfer coefficient [W/m^2K]
V	volume of the storage tank [m^3]
V_r	reference volume for the investment cost equation of the storage tank [m^3]
w	weighting factor of the composite indicator
α	exponent for investment cost of storage tank
η	efficiency

Subscripts

el	electric
th	thermal

Abbreviations

CHP	Combined Heat and Power
DD	Degree Days
DH	District Heating
DHN	District Heating Network
ELT	Electrical Load Tracking
FPO	Fixed Point Operation
HO	Hybrid Operation
ICE	Internal Combustion Engine
TES	Thermal Energy Storage
TLT	Thermal Load Tracking

1. Introduction

Combined Heat and Power (CHP) systems have become an attractive alternative for heating, hot tap water and electricity production with sizes ranging from a few kW_{th}, for individual or multi-family dwellings, to some MW_{th} with special attention to commercial and public buildings like hospitals, schools and offices.

CHP plants are particularly profitable in industrial sector but they are also suitable for applications in the civil/residential sector, where a combined and simultaneous use of electricity and thermal energy can be observed in a quite long period during the year and, in particular, in combination with residential District Heating Networks (DHN).

The diffused development of CHP plants is considered a strategic element to attain remarkable energetic, economic and environmental benefits. Several studies in the scientific literature have focused on the possible exploitation potential of CHP for the residential sector [1]. However, even though the combined generation of heat and power is in principle an highly efficient solution, compared with the separate production of electricity and thermal energy, it is necessary to consider in an accurate way the electrical and thermal load of the users, in particular an adequate level of heat demand close to the plant site: heat should be used in the proximity of the generation plant in contrast to electricity which can be fed into the grid.

In order to encourage people and communities to use CHP systems, after 1990 the governments of many countries have proposed many incentive policies and national programmes to support the CHP systems diffusion. Especially Netherlands and Denmark have adopted this policy, taking CO2 reductions into consideration too, [2]. Other countries as Spain, Italy, Portugal, France, Sweden and Finland have diffusely considered CHP plants both in the version of gas-fired or in the alternative version of biomass based CHP. In many cases the CHP has been supported by a conventional system (auxiliary boilers) for thermal energy production, in order to integrate the production in special cases (for example in cases of increased heat load requirements), [3].

The effects produced by the support mechanisms in the European countries have been widely studied in the scientific literature, both as regards the impact they had on the cogeneration evolution [4], both as regards the effectiveness in applying new technologies such as fuel cells [5] or the diversification of investments between the different states of Europe [6]. Some effects were positive as the system spread, optimization and cost reduction. Other effects were “distorted” because of the dominant role of economic elements. The main problems connected to the development of CHP power plants have been oversizing, downsizing with a consequent increase of size of the conventional thermal system, or very low share of production of CHP systems in comparison with the conventional boilers, used to integrate the thermal energy production.

The commercial and residential sectors play an important role for further efficiency improvements. In the EU, the energy consumption for space heating and water heating is about 20% of the total energy consumption. In this context, an increase in CHP plants connected to district heating is one of the ways of improving efficiency in the EU, and, in a recent study, Connolly et al. have identified the potential of DH in the EU and have proposed a new ‘‘district heating plus heat savings’’ scenario to reach an 80% reduction in annual greenhouse gas emissions by 2050, [7].

In the last years, mainly in Europe, CHP plants are well considered not only for the typical advantage obtained with respect to separated production of heat and electricity, but also for the opportunity to benefit the electrical grid balancing, especially in presence of intermittent renewable sources [8].

Many technical elements, related to the characteristics of heat and electricity demand, limit the diffusion of CHP plants in the residential sector. CHP plants would require, for optimal operational strategy, a fixed proportion between electricity and heat production. On the contrary load in residential sector is characterized by the following peculiar elements: very low intensity, limited duration, high temporal variability, low contemporary factor between daily electric and thermal load demands and highly unbalanced heat/electricity ratios.

The project of the CHP plant is also determined by several factors such as the type of user [9], weather conditions [10], available technologies [11], the financial support and obviously the characteristics of the load. Additional constraints are imposed by the possibility to recover thermal energy from industrial activities (electricity generation from cogeneration, incineration of waste, etc.) or to exploit the resources that the territory makes economically and geographically accessible (biomass, geothermal resource, etc.). The use of renewable sources is still growing, despite the enormous potential, as it involves the need for accurate energy and economic analysis, [12].

Several papers, like [13], propose analysis and methodological instruments for policy makers through which they can better orientate themselves among the different available technologies and the different scenarios determined by the specific climatic condition and the specific economic supply programme. Other contributions, like [14] and [15] analyze the problem of the correct management of CHP plants in the field of District Heating Networks.

In the various analysis available in the literature it is clear that the typical variations in the thermal load cannot be satisfied only by a CHP plant but an integration system is quite always necessary in order to support the operation of the CHP system: the size of CHP should be as large as possible, while the conventional boiler must be of reduced size. The use of Thermal Energy Storage (TES) system, discussed in the literature by some authors, can contribute to optimize the operational strategy, as [16] and [17].

Analysing the main applications of CHP units, it can be usually observed that systems do not operate at their full potential but mainly to cover the electrical self-consumption or the minimum values of the thermal load. Considering the very high variation of the thermal energy requirement, the major part of the thermal load is satisfied by means of the integration systems (in general a conventional boiler), while the CHP unit operates at partial load and for reduced times. Such management strategy does not follow the real purposes of the CHP plants because it does not take full advantage of the technology to reduce primary energy consumption, energy degradation (exergy losses) and pollutant emissions.

It is well known that the installation of a Thermal Energy Storage (TES) system and the use of a correct management strategy could aid in a meaningful way to reduce the exergy losses and to maximize the operating time of CHP. From an energy point of view, in a lot of specific application, the marginal role of the CHP unit appears to be clearly evident.

The large potential for energy saving by cogeneration in the building sector is scarcely exploited due to a number of obstacles in making the investments attractive. The analyst often encounters difficulties in identifying optimal design and operation strategies, since a number of factors, either endogenous (i.e. related with the energy load profiles) or exogenous (i.e. related with external conditions like energy prices and support mechanisms), influences the analysis. [18].

The aim of the present paper is to define an optimal operational strategy for the operation of a CHP system considering the influence of a reduced number of design variables including the operational strategy and the possible installation of a Thermal Energy Storage (TES) in order to increase the flexibility of the system. For this reason a multiobjective strategy is defined through the maximization of a composite indicator obtained considering different objective functions. The methodological approach proposed is tested with reference to a real case in which well defined heat load and a well defined plant are already available with the objective of maximising the share of operation of the CHP plants with respect to the conventional boiler.

2. CHP plants for civil/residential DHN: design and optimization

In order to perform an optimum design of a CHP plant, as for the majority of energy systems, three different levels can be identified, according to the description reported in Fig. 1. The three levels involve an increasingly detailed description of the system. The complete optimization problem can be stated as defining the synthesis of the system, the design characteristics of the components and the operating strategy that lead to an overall optimum of a well defined objective function.

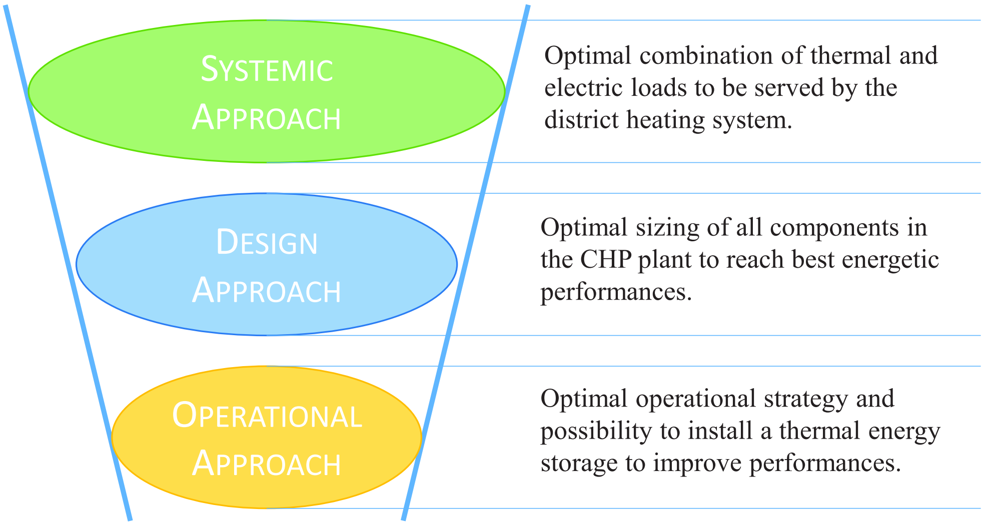

Fig. 1. The three levels of the optimization process

The first level of optimization concerns a kind of systemic approach. At this step the definition of the thermal and electrical loads to be served by the district heating network can be defined together with the plant configuration and the operational strategy. The aggregation of energy users with particular load characteristics, pursing an optimal aggregation of different type of buildings and energy user in order to obtain a specific load profile, appears to be the easiest way to obtain an optimum design of CHP plants because it simplifies the other two levels. In the case of civil and residential users like offices, hotels, hospitals, shopping centres and dwellings, the big issue is that all their profile shapes present increases and decreases of thermal request approximately in the same part of the day. Unfortunately this kind of approach is easier to be applied for industrial systems rather than civil/residential systems even if some significant improvements can be obtained [15].

The second level of the optimum design represented in Fig. 1 is the optimum design of the specific systems. In this case, the problem is the following: for a given heat and electricity load what is the choice and optimal sizing of the components of the power plant, in particular the size of CHP and thermal integration units, in order to maximize the share of operation of the CHP unit.

Each technology has advantages and disadvantages that must be related to the type of user served (required temperatures, average heat to power ratio, etc.) in order to properly choose the category and the sizing of the generation systems. The most used technologies are: reciprocating internal combustion engines (ICE), steam turbine systems, gas turbine systems and fuel cells [19-21].

The definition of the size and the correct matching of all the components are the real problem connected with the design and the operation of a CHP plant, in particular for what concerns the variable load requirements linked to the civil sector. At this step of the optimization process, the study of load duration curves is fundamental to optimally size and evaluate the opportunity to make the most of the energy saving potential of cogeneration and get important economic advantages too.

Due to the complexity and the large number of options and parameters available to such plants, finding optimized solutions for system design is a very difficult task.

A compromise between energetic and economic optimization has to be reached, [22]. Various optimization criteria have been suggested to this aim, like the mean annual gain, [23]. However, due to the technical and economic limitations and the several parameters that affect the operation and economy of the system [24], the capacity of a CHP unit is actually based on a case by case optimization, rather than the adoption of any rule of thumb. Even if methodological approaches for the optimum sizing of CHP units exist, they are rarely used.

The last level of the optimization process is the most complex because the thermal load of a CHP plant, meeting the needs of residential consumers, could be characterized by a large degree of irregularity. Once DH users and thermal generation units are defined, an optimum design strategy can only modify the time of power plant operation: this is a typical situation for many existing CHP-DHNs that need to be optimised. The choice of a particular operational strategy varies according to the size of components, thermal and electric requirements of utilities and the current political-economic context (possibility to feed into the grid, electricity sales remuneration, etc.). Moreover the importance of temperature of heat users and the availability of the various CHP technologies affect their operation and their efficiency.

The most common strategies for the operation are basically three: Thermal Load Tracking (TLT), Electrical Load Tracking (ELT) and Fixed Point Operation (FPO). A combination of them is frequent and is called Hybrid Operation (HO) strategy. In the TLT management, the thermal energy produced is always equal or less than that required by the user, depending on the CHP size. The ELT management has the main purpose to promote the total auto-consumption of electricity produced. The FPO strategy consists in running the CHP unit at its rated power to maintain maximum generation efficiency.

The HO strategy allows managing the system in order to satisfy the user requirements in the best economically and energetically manner, reducing waste and maximizing profitability. There are several possible options for HO: an example is to track the lower energy request between the thermal and the electrical load to avoid surpluses [25]; another way is to impose the ELT during the hours with lower gain from the electricity sale, or even to shut down the CHP, and use a cheaper thermal integration system. Therefore, the sizes of all components have to be closely linked to the specific management strategy: in particular, the sizes of a TES that can be a solution to shift the operation oriented at the heat demand to an operation led by the on-site electricity demand and reduce the load on the power grid [26]. In all modes, the optimal management is, as a rule, the one that allows obtaining a high number of equivalent hours of operation of the plant (3000-4000 h/year) and thermal/electrical limited surplus. In general, the higher the number of equivalent hours of operation of the CHP plants the greater the primary energy savings and the reduction of pollutant emissions but the overall efficiency of the power plant depends on the average load factor of the CHP unit. The economic gain is closely linked to the current incentive framework and uncertainty of prices. Even if optimization strategies exist, the results that can be obtained are not often particularly satisfactory from the energetic point of view.

3. Optimized operation strategy of CHP system

One of the most considered topics in the design of cogeneration units cooperating with district heating systems is to correctly define the size of the CHP unit and the size of the auxiliary systems (boilers) necessary to cover the peak load. This depends on the character of the duration curve of external temperature conditioning the heat demand for space heating and ventilation. The power rating of the CHP unit ought to be chosen according to the optimal coefficient of the share of cogeneration [27]. This coefficient defines the ratio of the maximum heat flux from the CHP to the maximum demand for heat but in general the size of the CHP is additionally influenced by the benefits of promoting high efficiency cogeneration or determined by the use of renewable energies.

Actually, in most cases, the real issue is to better exploit the CHP potential in existing plants. Assuming that the system has already been sized, the problem is to optimize the operational strategy of the CHP unit. In this way the optimum sizing of a TES system and the optimum management strategy of the CHP can be the only two variables that can be considered for increasing the operation of the plant. The analysis of load diagrams is essential to check the simultaneity of thermal and electrical loads: oscillating load profiles force the generation system to work in continuous transient conditions, with an overall efficiency that is reduced considerably and very high response times due to the system inertia. The installation of a TES tank is then fundamental to have more constant operation of the CHP plant and reduce the operating time of the auxiliary boilers. But the definition of its size is strictly linked to the operational strategy of the CHP unit. The covering of the variation of heat demands, at an individual building and multiple-building level, and also the way in which heat can be effectively supplied by CHP units with a thermal energy storage have been the topic covered in some recent papers as [28-29].

The principle applied by the authors is to maintain maximum efficiency of CHP operation by means of a combination of a HO strategy and an optimal-sized TES. In the proposed methodology, the design variables are the TES size and the operation strategy. The last one is defined according to some rules that are very influenced by the choice of that value. The HO strategy implies that the CHP unit operates in FPO, set at its rated power, but with some constraints.

The optimum design problem can be analytically described as the maximization (minimization) of a well defined objective function connected to the plant operation submitted to the various constraints. In particular the rated thermal power of the CHP unit, P_{th}^{CHP} and the current thermal level of the maximum value of the storable energy E_{max}^{TES} (TES size). The operation of the plant can be referred to each of the 8760 hours during one year. Another element important to describe the operational strategy of the plant is represented by the mode of operation described according to the following function:

$$(CHP)_i = \begin{cases} 0, & \begin{cases} (CHP)_{i-1} = 0 \\ E_{th,i-1}^{TES} - E_{th,i}^{load} \geq E_{min}^{TES} \end{cases} \\ 1, & \begin{cases} (CHP)_{i-1} = 0 \\ E_{th,i-1}^{TES} - E_{th,i}^{load} \leq E_{min}^{TES} \end{cases} \\ 1, & (CHP)_{i-1} = 1 \end{cases} \tag{1}$$

where $(CHP)_i$ is the current status of the CHP unit (0 = off and 1 = on) and E_{min}^{TES} is the minimum value of the storable energy. According to these constraints, no heat is wasted (only thermal losses of the tank) and the CHP unit operates at its maximum efficiency for the highest possible number of hours in succession, until the tank is full and cannot store additional energy.

Then, the CHP unit is off and the thermal load is satisfied by the heat stored until it reaches its minimum: this condition ensures more constant operation and the reduction of ramps could determine a longer life of the components of the plant. To have a comprehensive view of the performances of the CHP plant, in the present methodology, some objective functions or indicators can be considered. The first considered indicator is surely the first Law efficiency of the system,η^I defined as:

$$\eta^I = \frac{\sum_{i=1}^{8760}\left(E_{th,i}^{boil} + E_{th,i}^{CHP} + E_{el,i}^{CHP}\right)}{\sum_{i=1}^{8760}\left(E_{th,i}^{CHP}/\eta_{th,i}^{CHP} + E_{th,i}^{boil}/\eta_{th,i}^{boil}\right)} \tag{2}$$

where $E_{th,i}^{boil}$ is the thermal energy produced with the boilers, $E_{el,i}^{CHP}$ is the electrical energy produced by the CHP unit, $\eta_{th,i}^{CHP}$ and $\eta_{th,i}^{boil}$ are the thermal efficiencies of the CHP unit and boilers respectively. Considering only this indicator, a maximization of the operating hours of the boilers could be obtained but this is not correct from the point of view of the CHP system.

A second remarkable indicator is the Second Law efficiency of the systems, η^{II}, defined as:

$$\eta^{II} = \frac{\sum_{i=1}^{8760}\left(E_{el,i}^{CHP} + \left(E_{th,i}^{CHP} + E_{th,i}^{boil}\right) * \left(1 - T_o/T_{supply}\right)\right)}{\sum_{i=1}^{8760}\left(E_{th,i}^{CHP}/\eta_{th,i}^{CHP} + E_{th,i}^{boil}/\eta_{th,i}^{boil}\right)} \tag{3}$$

where T_o and T_{supply} are the reference temperature and the network supply temperature. This indicator leads to maximize the operation of the CHP, because the exergy losses of the boilers are surely more remarkable.

A third indicator is represented by the hours of operation of the CHP unit, h_{op}, defined as:

$$h_{op} = \sum_{i=1}^{8760}(CHP\,)_i \tag{4}$$

Another important parameter is represented by the number of starts and stops of the CHP unit, indicated as N:

$$N = \sum_{i=2}^{8760}\left|(CHP\,)_i - (CHP\,)_{i-1}\right| \tag{5}$$

Other operational indicators are the thermal energy produced by boilers, E_{th}^{boil}:

$$E_{th}^{boil} = \sum_{i=1}^{8760} E_{th,i}^{boil} \tag{6}$$

and the thermal losses of the TES, E_{loss}^{TES},:

$$E_{loss}^{TES} = \sum_{i=1}^{8760} E_{loss,i}^{TES} \tag{7}$$

where $E_{loss,i}^{TES}$ is the TES thermal loss in the *i-th* hour. The thermal losses obviously depend on the type of storage tank considered. The last element that can be considered is the investment cost of the TES system, C.

This can be obviously connected to the volume of the storage system, according to a law of the type:

$$C = C_r\left(\frac{V}{V_r}\right)^{\alpha} \tag{8}$$

where C_r is the reference cost, V_r is the reference volume, α is the exponent of cost increase and V is the volume tested. The cost has been calculated according to the exponent α=0,30 of the formula extracted from [30]. According to this hypothesis, the profile of specific cost is illustrated in Fig. 2 where the reference volume (V_r) is one cubic meter and C_r is its reference cost.

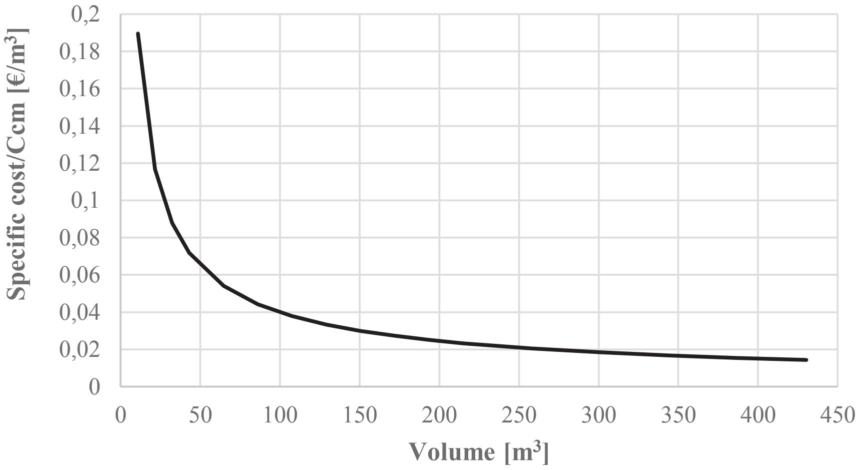

Fig. 2. Specific cost for different volumes of TES

All those objective functions are considered significant to give an additional premium or penalty to the plant configuration. The energetic and economic functions are calculated for each of the possible sizes of the TES; but only one value can be identified as the optimum.

The smallest volume permits to have the lowest losses and investment costs while the biggest one permits to have the maximum value of h_{op}, i.e. highest energy savings and pollution reduction. A compromise has to be reached between all the previously considered objectives [31] and defining a composite indicator. The composite indicator, I, that needs to be maximised, is defined in the generic form as discussed in the section dedicated to the multiobjective optimization of [32], considering also the approach reported in [33]:

$$I = \sum_{i=1}^{N} I_i = \sum_{i=1}^{N} \pm\left(w_i f_i(x) + F_i\right) \tag{9}$$

where $f_i(x)$ is the i-th parameter, w_i is the weighting factor, F_i is a constant, dependent for each one of the parameter considered on the parameter range and the sign $\pm$ depends on the single objective function considered ("+" to maximize and "–" to minimize). The weighting function w_i and the constant F_i can be defined as:

$$w_i = \frac{1}{f_i^{max} - f_i^{min}} \tag{10}$$

$$F_i = -\frac{f_i^{min}}{f_i^{max} - f_i^{min}} \tag{11}$$

where f_i^{max} and f_i^{min} are, respectively, the maximum and minimum value observed for the *i-th* parameter. The definition of these two values depends on the purpose of the composite indicator used as objective function of an optimum design method. It can be a comparative analysis between different configurations of the same system or an optimization compared with the best available technology. In the first case, f_i^{max} and $f_i^{min}$are the highest and lowest values achieved for the *i-th* parameter comparing all the analysed configurations. For the various analysed configuration, the best one will be the one corresponding to the maximum value of a composite indicator, obtained combining energetic and economic objective functions. In most of cases, an energetically optimal range is defined while the exact size value can be obtained through a further economic analysis. This approach can be applied to a multi-criteria analysis considering a wide range of energetic or economic parameters.

4. Characteristics of DH thermal loads: analysis of a case study

The case study, presented in this section, is important to better understand the problems connected with the development of the CHP plants for what concerns a correct definition of the TES size and the optimal management strategy. Even if in the analysis of CHP systems connected to DH network, each case has a specific connotation and specific loads, some general elements can be evidenced. The authors have used the data acquired on the real plant that can be considered representative of such a kind of systems.

4.1 System description

The CHP-DHN under study is located in a town located in the north of Italy, Turin. The network users are the residential buildings in the area, in particular, the following buildings are served:

- a complex of 640 civil apartments distributed in 31 different buildings (total volume served estimated to be about 180000 m^3);
- a building with offices and service station (volume served 22000 m^3).

The total heat demand peak is about 2500 kW$_{th}$. This value is calculated considering the typical peak load conditions of the town and a characteristic load profile. The hot water produced by the system, at a temperature of 75-80 °C, is used both for sanitary and for heating purposes. The electric power installed is about 2500 kW$_{el}$ (310 kW$_{el}$ are required for the service building). In the current configuration, the thermal power is generated by a natural gas internal combustion engine with rated power of 970 kW$_{el}$ and 1160 kW$_{th}$. In the geographic area considered, the cold season is extended from 15th of October to 15th of April, being this imposed by Italian Law.

With the aim of supporting the operation of the CHP unit, in order to follow the variations in heat demand, two natural gas-fired boilers are installed: a condensing boiler with a nominal power of 900 kW$_{th}$ and a conventional auxiliary boiler with a nominal power of 2600 kW$_{th}$ (an additional auxiliary boiler of 2600 kW$_{th}$~~.~~ is installed for safety reasons). Even if the maximum thermal power required is 2500 kW$_{th}$, the maximum installed thermal power is about 4650 kW$_{th}$. (7250 kW$_{th}$ considering the safety boiler too). A schematization of the plant is provided in Fig. 3.

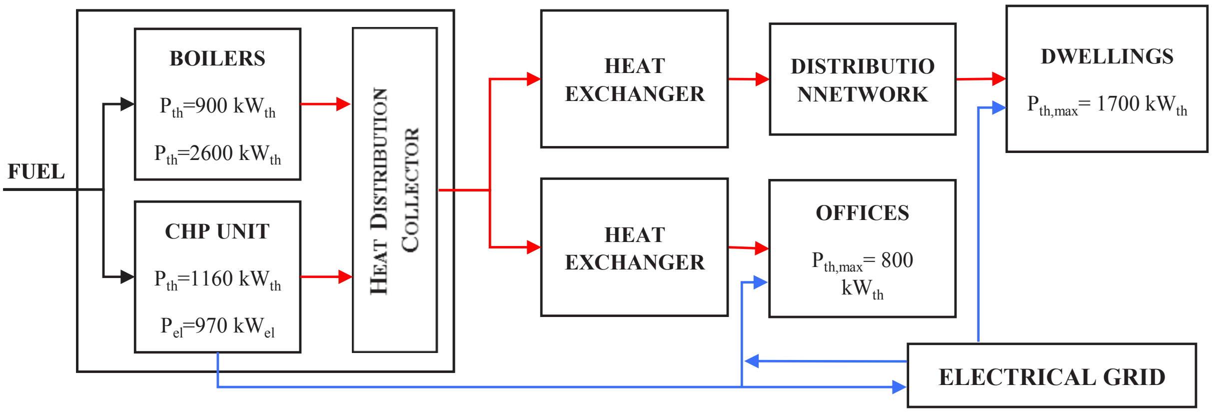

Fig. 3. Simplified scheme of the system analysed

Additional details about the system can be obtained analyzing other publications of the authors ([33] and [34]). The heat distribution system is characterized by pressurized water. In design conditions, the following data can be considered: inlet pressure at 4,5 bar with return at 4 bar; inlet flow temperature at 75 °C with return at 62 °C.

The distribution network is branched/meshed direct type without exchange substations. The network consists of a double pipe (inlet flow and return), and spreads to an overall length of approximately 2000 meters. The pipes are made of an inner steel tube, embedded in an insulation layer of polyurethane foam, all externally protected with a sheath of high-density polyethylene.

The network is equipped with a remote monitoring system, designed to remotely observe the system energy flows, the consumption data of the users and the generation data of the CHP plant. It is connected to the measuring instruments using radio waves. The data transmitted from each measurer to the signal control unit are sent on the web, through corporate network, to a virtual portal through which it is possible to display the measures of the connected instruments. The presence of a remote monitoring system of the CHP plant and utilities can help in the management as it allows viewing online consumptions, temperatures and flow rates in various parts of the network and promotes rapid identification of any operation problems.

4.2 Analysis of the heat demand profiles

Any set of buildings, as well as a single building, never has a constant heat demand during the year: during summer time only energy for domestic hot water is required while during winter also the load due to space heating has to be considered. The heat demand profile is made complex by some daily factors: the level of building occupancy, occupant behaviour and weather conditions (in particular, temperature and solar radiation). Fig. 4 shows the typical variation of the thermal load and the corresponding external temperature for the analysed case that can be considered representative of the typical load profile of district heating systems for civil and residential buildings. The remote monitoring system allowed to study the dynamic behaviour of the system for a whole year: the data of a whole year, from 1st July 2015 to 30th June 2016 have been acquired and considered. One-hour interval has been chosen as time step for the acquisition of data. The load profile changes during the week depending on the considered day (this is mainly due to the presence of offices that reduces the load requirement during the weekend and during the night) and strong hourly variations that depend on the switching on and off at certain times of the heating systems.

A more effective vision to obtain information regarding the operation of a plant may be given instead by a duration curve, such as that of Fig. 5 for the plant concerned. Such a curve allows to understand what the most common operating range of the system is and thus properly size the production and storage systems of a DH plant. In this case, as well as in most of civil and residential DH systems, more than 70% of the heat demand is less than half of peak demand. Accordingly, this kind of users requires very flexible thermal production systems.

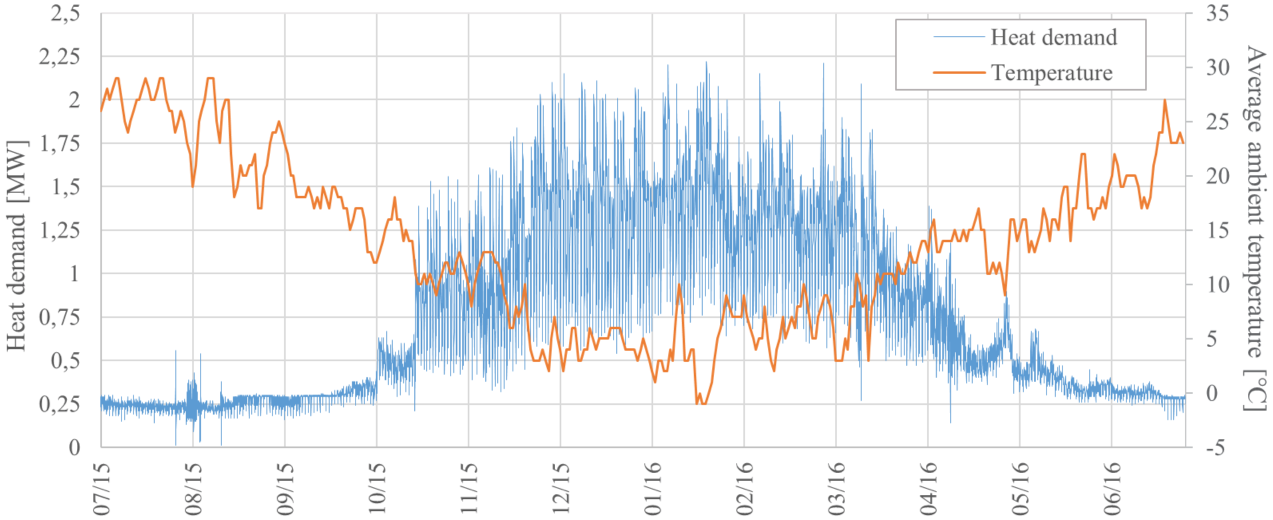

Fig. 4. Annual heat demand and average ambient temperature

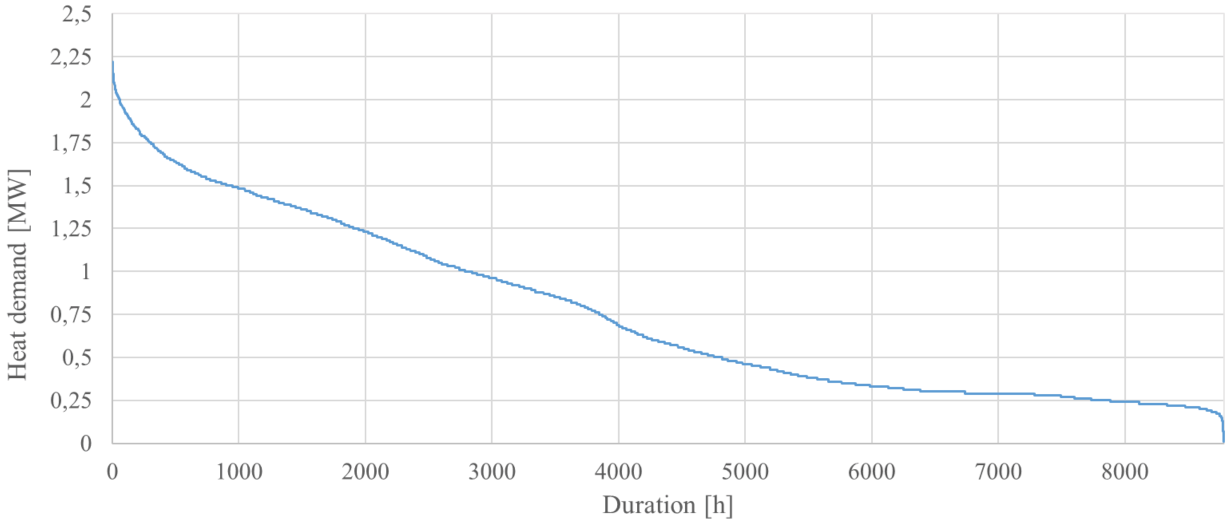

Fig. 5. Annual thermal load duration curve

The separation of the thermal load profiles of the types of users, shown in Fig. 6 for the case examined (one week in January, from Monday to Sunday), helps to understand the possible extent of the variation. The graph shows the typical profile with two peaks of heat demand of the dwellings that is repeated during the week and the load profile of the offices that instead is not present over the weekend. In addition, the times of the peaks and the troughs of both profiles tend to coincide and this results in a further increase of the oscillation of the thermal request.

This situation occurs in many DH systems and is the main reason why the CHP units often work away from the nominal power, getting low efficiency and emissions reductions, and require the continuous support of boilers or other integration systems. One way to solve this problem is to phase shift the request of one of the load types through a TES system and make sure that the peaks of one profile go to fill the troughs of another, thus obtaining a more constant overall heat demand.

By grouping the months based on similar monthly average external temperatures, it was possible to obtain a representative average weekly load for each of the five different periods in which the whole year was divided in Fig. 7. The profiles were obtained by averaging of two or three months, by the hour, the total heat load of the user to highlight the variation between the above-mentioned periods. It is evident that the consumption of hot water in the two warmer periods generates much more regular profiles compared to the profiles of the heating periods that, however, appear to be very similar to each other even if scaled by a factor. The amplitude of possible oscillations, which can occur in the different groups of months considered, is also different for the winter and the summer, as shown in Fig. 8. When heating is required, the trend of the outdoor temperature strongly affects the thermal load. On the contrary, in the warmer months, the load fluctuations are significantly reduced since the only possible effect of the external temperature variations is to influence the temperature of water coming from the waterworks.

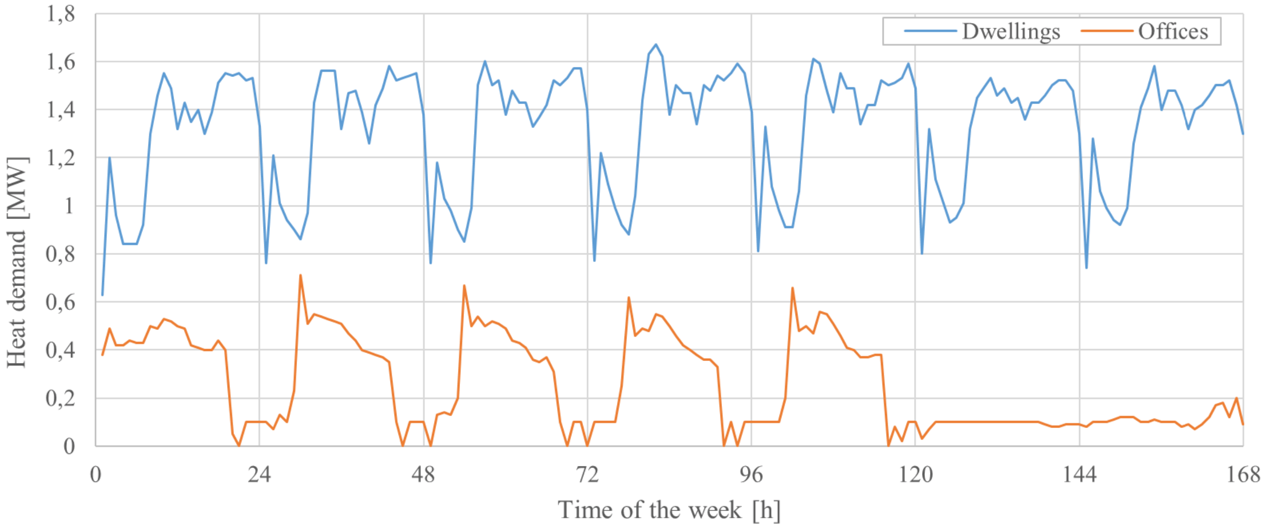

Fig. 6. Typical weekly heat demand for different types of users

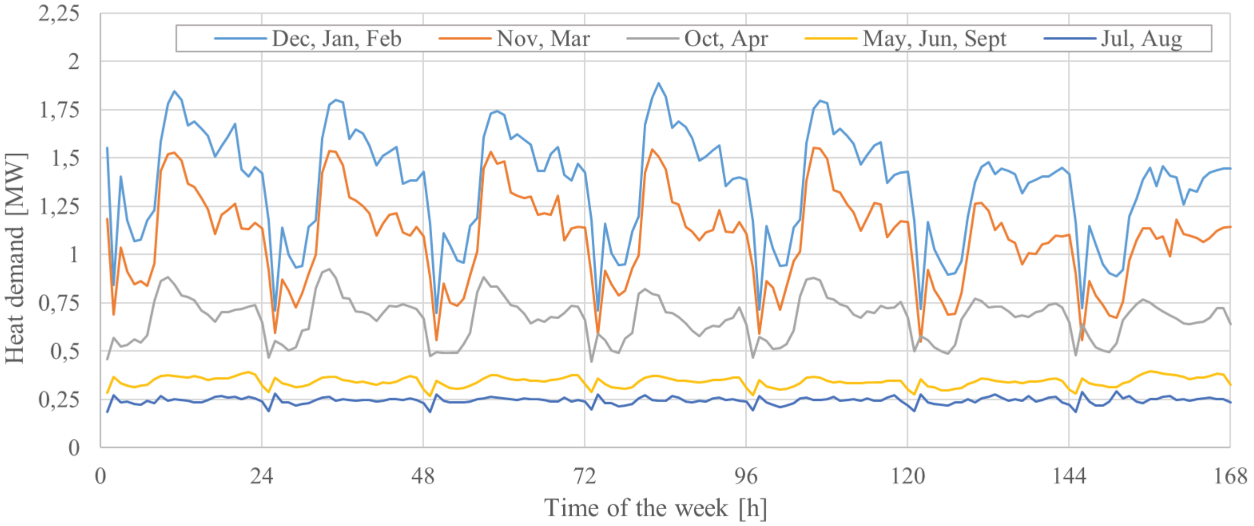

Fig. 7. Average weekly heat demand for group of months with similar average temperature

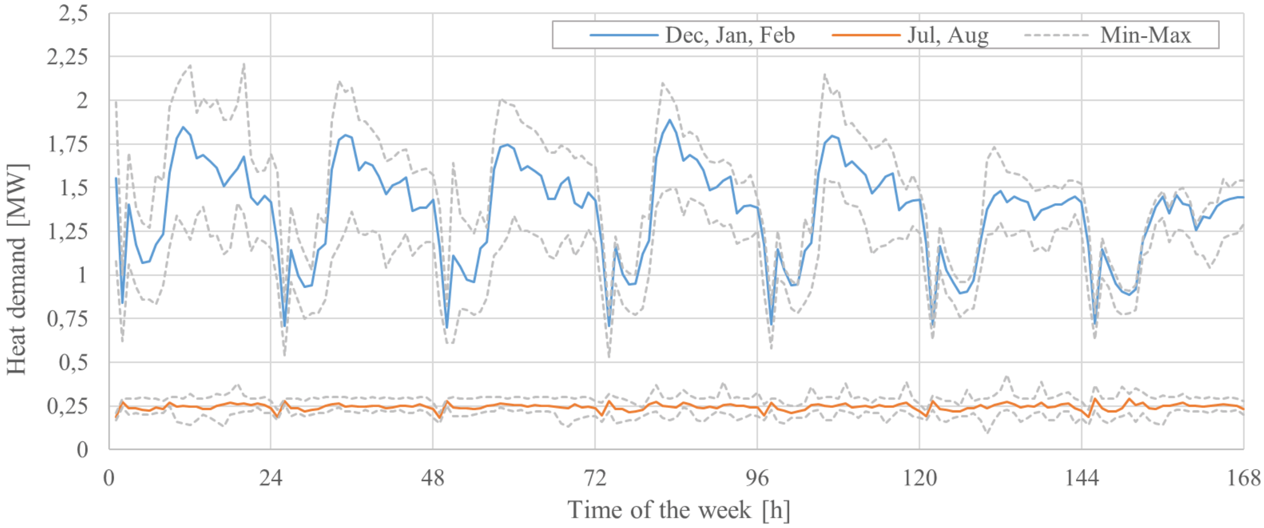

Fig. 8. Amplitude of the oscillation of the heat demand for an average summer and winter week

5. Optimization of the operational strategy in the analysed case

According to the HO strategy previously described in section 3, a possible optimized scenario for the analysed district heating system has been simulated in which a TES is installed: the CHP unit operates at its rated power while boilers work only to cover the daily heat peak load, with priority for the condensing boiler rather than the traditional one (the last one has not a significant role in satisfying the heat needs). Therefore, the CHP unit works in FPO until the TES is filled at its maximum energy level by the excess heat produced. This strategy permits to make no waste of heat during the whole year and to always operate the CHP unit at its maximum efficiency, even outside the heating season. The optimal size of the TES has been tested considering an increasing value of the maximum stored energy from 250 to 10000 kWh, corresponding to a volume varying from 10,7 to 415 m^3. The volume of the tank for TES has been calculated considering a cylindrical hot water tank with height equal to its diameter that reaches a maximum average temperature of 90°C at the end of charging period and a minimum average temperature of 70°C at the end of the discharging period. The temperature difference hypothesized (T_{max} - T_{min} = 20°C) permits to accumulate 23,25 kWh for each cubic meter of stored water. The thermal losses of the tank to the ambient have been estimated to be proportional to its envelope area (25 cm of insulation) and an estimated value of the heat transfer coefficient, typical of such a kind of applications ($U = 0{,}12 W/m^2K$) considering the average storage temperature (80 °C) with the ambient at its yearly average temperature (15°C), [35].

Fig. 9 shows annual and specific losses as a function of the storage volume, according to the hypothesis. When TES sizes are lower than the rated thermal power of the CHP unit and the request is only for hot tap water (i.e. warmer season), boilers produce the most part of the thermal energy.

Fig. 10 explains this concept: the number of starts and stops of the CHP unit is low (< 1500) for little storage volumes because boilers operate for long periods as it can be seen by the respective low hours of operation (< 3500). Increasing the TES size, the number of starts and stops reaches a peak and decreases, indicating operation conditions less stressful for the CHP unit: the bigger the storage volume the higher the hours of continuous operations.

Lower storage volumes correspond to an increase of the thermal energy produced by boilers, characterized by a decreasing efficiency working far from nominal conditions. However, the increase of operation hours of the CHP unit does not correspond to a monotonous decrease of the irreversibility: small TES sizes can determine some particular conditions in which boilers work with a very low annual average efficiency while large TES sizes produce an increase in thermal losses of the tank. In the analysed case, a peak in irreversibility occurs at about 30 m^3, as showed by Fig. 11, and, after reaching a minimum value, irreversibility increases again.

The calculation indicates that for reducing the exergy losses, it is necessary to avoid very frequent start and stop of the CHP plant. Obviously very frequent start and stop of a plant could have an important impact on the reduction of the operating life of the plant This could produce an additional economic cost, even if the influence of start and stop on the overall performance in general varies significantly from engine to engine.

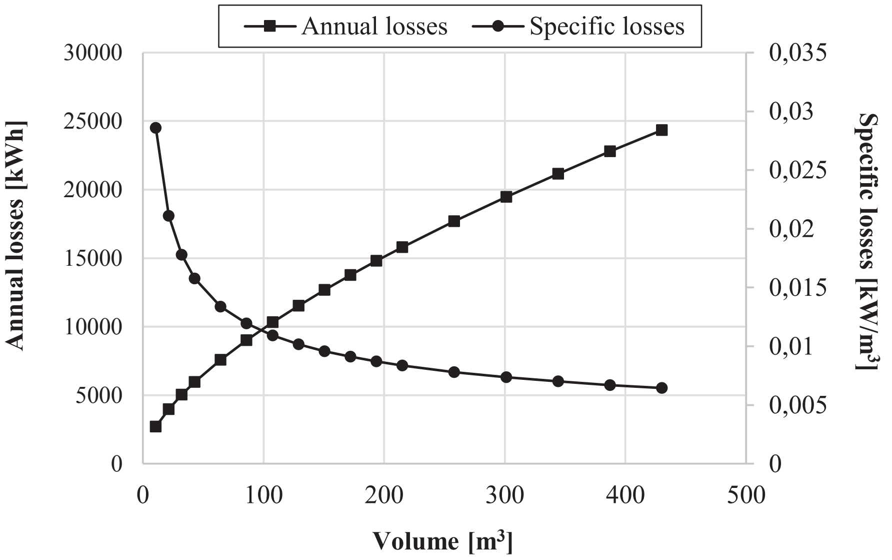

Fig. 9. Annual losses and specific losses of the TES

Two more general indicators can resume the overall behaviour of the system: First and Second Law of Thermodynamics efficiencies. In Fig. 12, the first indicator demonstrates how the average efficiency of the power plant (CHP unit and boilers) decreases of about four percentage points for little TES while the second indicator has a growing profile in parallel to the increase of the share of the CHP. However, these two profiles have not an asymptote because of the increase of losses for greater storage volumes. According to the methodology explained in section 4, to reach a compromise between all the aspects considered for the optimum design, a composite indicator has been used for the analysed case and the results are reported in Table 1. The profile obtained in Fig. 13 shows that a peak occurs at about 3000 kWh of energy stored, corresponding to a volume of the tank of about 130 m^3. Observing the profile shape, the presence of a maximum value of the objective function I is evident in the range in which the size of the tank is between 100 m^3 and 150 m^3. The exact value can be obtained by an economic analysis, taking into account the uncertainty related to the fuel and electricity sale price.

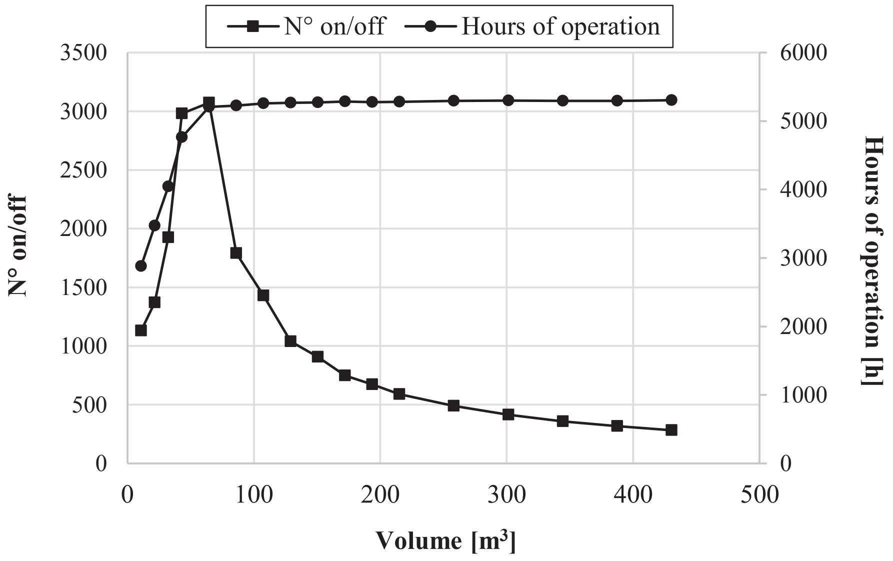

Fig. 10. Number of starts/stops and hours of operation of the CHP unit

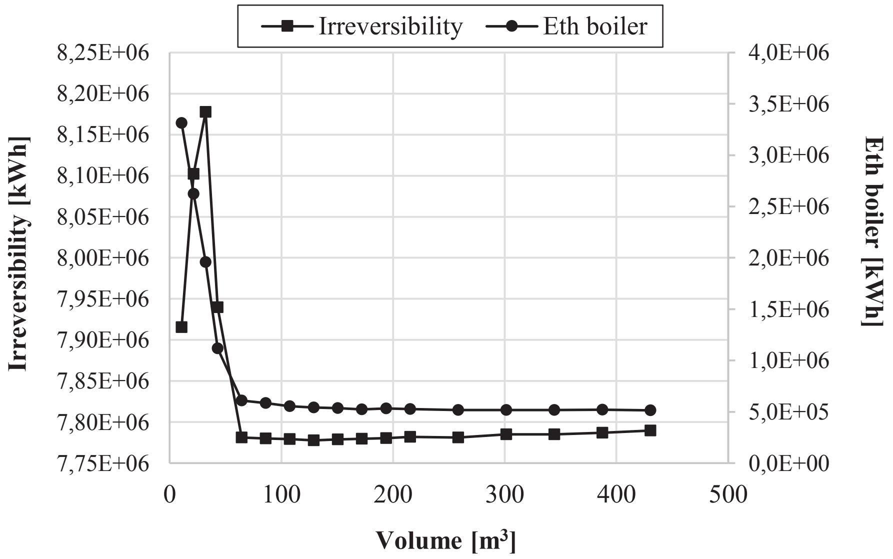

Fig. 11. Annual irreversibility and energy produced by the integration units

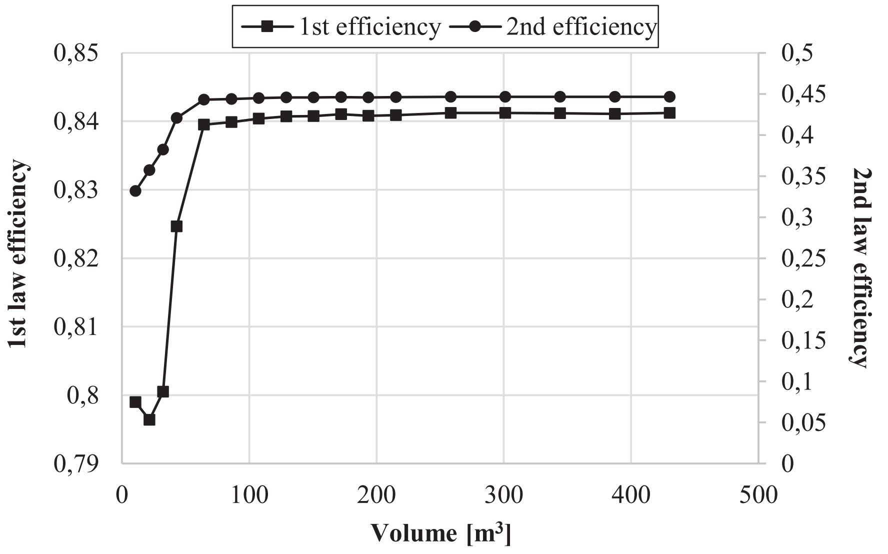

Fig. 12. First and second law of thermodynamics efficiencies

Table 1. Values for the composite indicator for each TES volume tested

Volume [m^3]	I	Volume [m^3]	I	Volume [m^3]	I
10,76	-1,247	107,60	1,681	258,24	1,442
21,52	-0,849	129,12	1,730	301,29	1,327
32,28	-0,392	150,64	1,681	344,33	1,211
43,04	0,594	172,16	1,664	387,37	1,093
64,56	1,279	193,68	1,588	430,41	1
86,08	1,631	215,21	1,541		

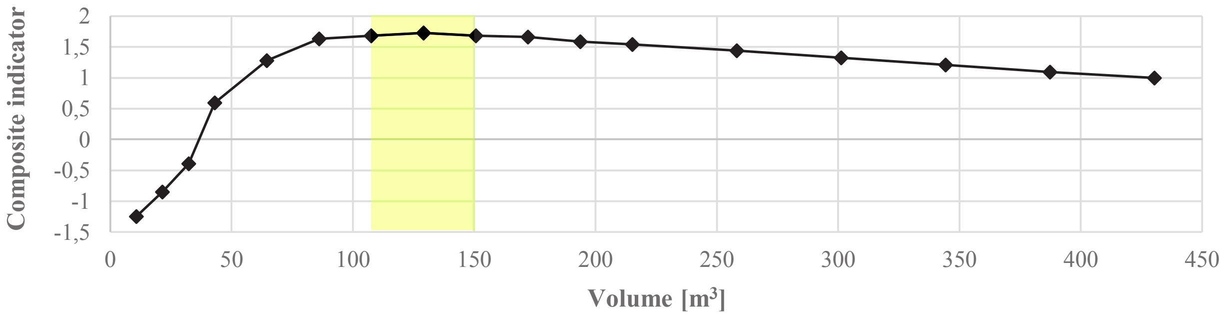

Fig. 13. Value of the composite indicator I for the different sizes of the TES

For the optimal size of the TES, the parameters taken into account are summarized in Table 2 and the system behaviour for three significant weeks, during the year (one corresponding to summer time, one for mid season and one for winter time) is showed in the following charts. As it is evident, the optimal number of CHP starts and stops is given by a compromise of all parameters. Some constraints can be imposed to consider a maximum if ensuring a predetermined number of life years for the CHP unit is necessary. In the case analysed, 520 periods of CHP operation occur (1040 switches on to off or viceversa), the most during the warmer season when there is no request for space heating. This issue is clearly shown in Fig. 14 where the thermal load profile, the thermal energy by the CHP unit, by boilers, by the TES (positive if accumulated, negative if released) and the thermal energy stored profiles are illustrated for a week with low thermal load. The hot tap water load is too low compared to the rated thermal power of the CHP unit therefore the presence of the storage tank is fundamental to make no waste of heat, even if the CHP unit operates for really short time periods. The same profiles are illustrated in Fig. 15 for a week with medium thermal load, which demonstrate how the energy stored in low load periods can help to satisfy the load peaks without switching on the boiler. On the contrary, as evident in Fig. 16, in coldest periods, the presence of the TES cannot avoid the use of boilers because the user load is quite always higher than the rated thermal power of the CHP unit. However, it helps to not shut down the CHP unit when the thermal load is lower than its rated thermal power.

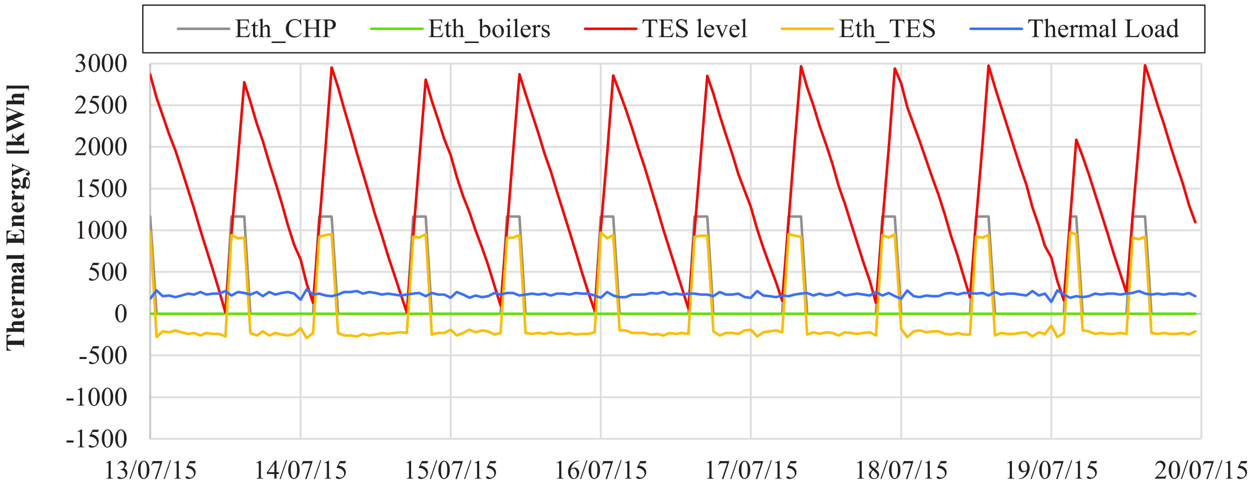

Fig. 14. System behaviour for low thermal load

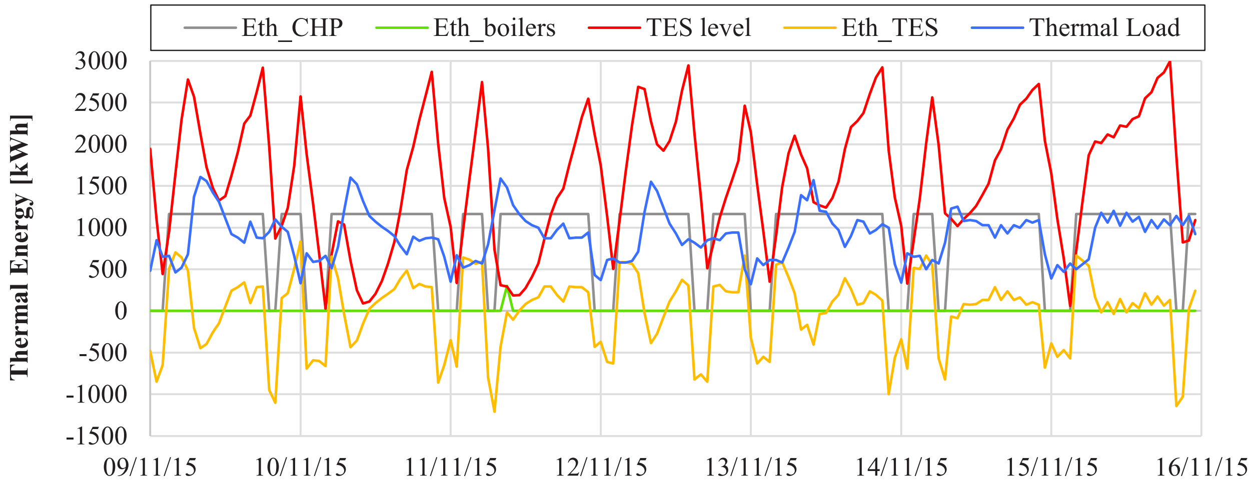

Fig. 15. System behaviour for medium thermal load

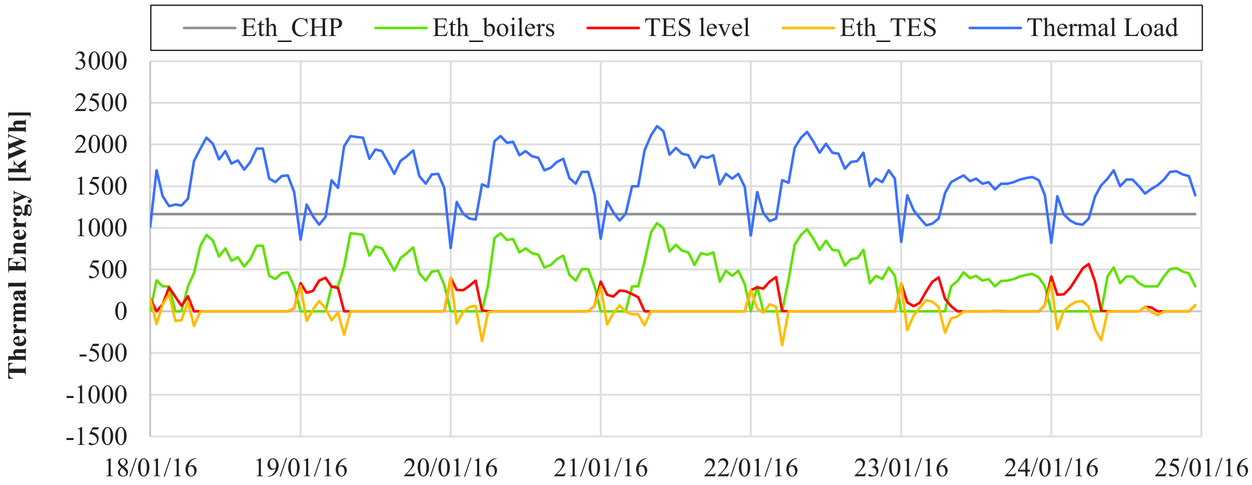

Fig. 16. System behaviour for high thermal load

To understand the effect of the optimized strategy, with TES, calculating similar performance parameters is necessary in an alternative scenario, without TES, in which the CHP unit is able to meet loads up to 20% of its rated thermal power and each boiler to 30% of its rated thermal power. These constraints imply that the wasted heat is not only the tank thermal loss but also the surplus heat generated by the CHP unit or by boilers when they can not further modulate. The results are summarized in Table 2. Analyzing the data it is possible to observe that the optimized strategy leads to a reduced operation time of the auxiliary boiler and this permits a meaningful increase of the second Law efficiency of the system that increases from 0,354 to 0,446: this means a more correct use of primary energy. Similar considerations can be evidenced considering the increase of the First Law Efficiency and the sensible reduction of the heat wasted (from 163000 kWh to 11500 kWh). Moreover, increasing the production of thermal energy by means of CHP leads to a sensible increase of the annual electricity produced, according to the data provided in Table 3.

On the other hand, the number of CHP operating hours does not differ so much, considering the two operational strategies, as already seen, in the cold season, the presence of the TES does not cause significant effects, while in the other seasons the CHP unit operates in TLT and generally works at partial load. So it is possible to conclude that considering the conventional strategy, the number of on/off cycles is zero (maintenance period are not considered) but the thermal efficiency and, mostly, the electrical efficiency of the CHP unit drop significantly. The absence of the TES also involves some heat wasted to the environment that would otherwise be avoided since most of the burners of boilers cannot work under 30% of their nominal power, unless a control system is not present to limit the generation of the CHP and to reduce the heat surpluses.

Table 2. Results of the parameters taken into account by the tested operational strategies and comparison

	1st law efficiency	**2nd law efficiency**	**Heat wasted [MWh]**	**Production of the auxiliary boiler [MWh]**	**CHP hours of operation [h]**
Optimized Strategy	0,84	0,446	11,540	541,345	5268
Conventional Strategy	0,74	0,354	163,145	880,395	5105

Table 3. Electricity produced with the two different regulation strategies

	For the whole year [MWh]	For the heating period only [MWh]
Optimized Strategy	511,615	388,859
Conventional Strategy	406,404	349,477

6. Conclusions

The application of CHP technology in the civil/residential sector is often problematic: the thermal and electrical loads vary in a meaningful way from hour to hour, from day to day, creating many difficulties for the simultaneously efficient fulfillment of loads. It is possible to frequently see heat wasted and systems operating with low efficiencies (mainly second Law Efficiency). In this way, the potential of CHP systems for energy saving is not fully exploited. In this context, the study of methods for optimizing the operation of existing systems becomes crucial for reaching an energy benefit and maintaining a low economic impact.

The authors have shown in the paper how, considering an existing CHP plant connected to a District Heating Network, the use of a well-sized TES and a correct operational strategy can help to operate in a constant way the CHP unit, increasing the share for the thermal production and increasing the energy efficiency. The procedure is based on the application of a particular objective function in the form of a dimensionless composite indicator, considering different single typical indicators with a multi-objective perspective. The methodology has been tested with specific reference to a real case. In the examined case, considering a CHP unit of 970 kW_{el} and 1160 kW_{th} nominal power and two auxiliary boilers of 900 kW_{th} and 2600 kW_{th} of nominal power, the installation of a TES with a volume in the range between 100 and 150 m^3 permits to obtain sensible increases in the Second Law Efficiency of the system (from 0,35 to 0,44) and a sensible reduction of the thermal energy waste. The absence of the TES would imply the need to activate in a great number of occasions the integration systems (boilers) in order to meet the request of hot water.

The analysis made by the authors though if applied to a single case study, shows the possibility of obtaining consistent energy saving (the energy waste can be reduced in a consistent way) and a more correct energy use (the auxiliary boilers reduce the production of about 30%) in the operation of existing plants only considering an optimal sizing of a storage system.

The calculation indicates that for optimizing the operation of the plant, from a purely technical point of view, the increase of start and stops of the CHP plant is necessary and this could produce an additional economic impact that need to be considered in further analysis. On the other hand, the CHP plant can also operate in more stable conditions.