Optimum sizing and operational strategy of CHP plant for district heating based on the use of composite indicators

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Abstract

The aim of the paper is to discuss the possible use of Combined Heat and Power (CHP) plants and to highlight some abnormal effects, generated by the available support mechanisms, both in sizing and management and to propose guidelines for defining optimal operational strategies of CHP power plants. Some composite indicators are proposed to give a more comprehensive assessment of the performances of a plant, for the design and optimization phase and for a possible approach to support mechanisms. A new composite indicator is introduced in order to assess the benefits of different scenarios. The method is tested with reference to a case study: a medium size district heating system, powered by a CHP plant supported by conventional auxiliary boilers. Data coming from a real plant equipped with a remote monitoring system are analyzed. Operating data of a typical month are used in order to test the approach for the reference system. The paper shows how the use of the defined composite indicators can modify in a meaningful way the operating strategy of the CHP, increasing a lot the share of thermal energy produced with the CHP unit with respect to the conventional boilers.

Keywords: Combined Heat and Power; District heating systems; Exergy analysis; Quasi-steady model; Composite indicators; Optimization

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Nomenclature

E	energy [kWh]
f	energy factor
h	hours [h]
I	exergy losses [kWh]
K	cost
P	power [kW]
Q	thermal energy [kWh]
Q^*	thermal energy coming from renewables [kWh]
t	time
U	utility function
w	weight factor for defining the utility function
W	electric energy [kWh]
Z	capital cost
ε	quantification factor for thermal energy value
γ	quantification factor for input energy value
γ^*	quantification factor for input energy from renewable energy value
η	efficiency
Ψ	composite utility function considering exergy losses
Ψ'	composite utility function considering exergy losses and renewable energy input
Ψ''	composite utility function considering different energy output

Subscripts

aux	required for the operation of auxiliary systems
dn	to the heat distribution network
e	relative to the environment
el	electric
fuel	of the fuel
GN	natural gas
in	input
k	referred to the k-th component of the system
n	net
out	output
P	primary energy

r	referred to the r-th main part of the system
th	thermal energy
u	distributed to the end-users

Abbreviations

CHP	Combined Heat and Power
DH	District Heating
DHN	District Heating Network
PEE	Primary Energy Efficiency
PEF	Primary Energy Factor
PES	Primary Energy Saving

1. Introduction

The economic impact and the environmental benefits generated by the application of cogeneration in the industrial sector led to the spread of this technology to civil and residential complexes. For this reason, 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.

In order to encourage people to use CHP systems to generate simultaneously heat and electricity, after 1990 the governments of many countries have proposed many incentive policies and national programmes to promote the CHP systems. Especially UK, Netherlands and Denmark had adopted this policy, taking CO_2 reductions into consideration. Other countries as Spain, Italy, Portugal and France have diffusely considered the use of gas-fired CHP, while countries as Sweden and Finland developed biomass based CHP. The advantages of small plants (differentiated into micro-CHP and small-CHP according to maximum electrical power required [1]), compared to conventional systems, in terms of energy efficiency [2], the environmental impact [3] and economic costs [4] are still object of study and great interest in the scientific literature. The market offers several types of mini-cogeneration-plants. CHP with conventional combustion engine, micro-turbines and fuel cells are the most common ones [5]. In contrast, larger plant sizes, if well designed, provide great economic and energetic advantages because they allow the application of well-established technologies such as internal combustion engines, steam turbines and gas turbines.

The project of the CHP plant is determined by several factors such as the availability of fuels that can feed the system [6], weather conditions [7], available technologies [8], the financial support context and obviously by the characteristics of the load that must be satisfied. Cogeneration is also preferred to heat and electricity separated production for the opportunity to benefit the electrical network balancing, especially in the presence of intermittent renewable sources with net production drops during the winter season. However, the existence of financial support mechanisms is often the more relevant element of promotion of CHP plants, instead of the attention to a real efficiency increase of the national energy system. In this framework, a critical point is the ability to plan an optimal control strategy to regulate the interactions between the various components operating in the energy systems, like CHP systems and fluctuating renewable energy sources. The topic is covered in several papers available in the literature, like [9], [10] and [11], taking into account the different perspectives of the problem.

The technical aspects that limit the spread of CHP plants in the residential sector are related to the characteristics of the demand for heat and electricity, i.e. very low intensity, limited duration, high temporal variability, low contemporary factor between daily electric and thermal load demands and highly unbalanced heat/electricity ratios.

Except in the case of district heating systems, residential users require small plants which have not yet achieved the scale economies that make them competitive in current market conditions: the specific investment costs grow highly with decreasing size and the return on investment is delayed by the reduced number of operation hours (typically smaller than 2,000 annual equivalent hours) [12]. By contrast, the sector of public facilities is more suitable to be powered by CHP systems, especially hospitals, sport centres with swimming pools and hotels with spa because of high and constant loads during the year.

Even if the use of CHP for district heating networks has been largely supported, analysing the main applications of CHP units, a frequent observed situation is 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 most of the thermal demand is met by integration systems (in general a conventional boiler). Such management strategy does not follow the real purposes of the CHP connected to district heating networks because it does not take full advantage of the technology to reduce primary energy consumption and pollutant emissions. Another issue that complicates the system management also lies in the sizing of power generation systems: boilers are significantly oversized and are often forced to work at very low partial loads because of the large fluctuations in the heat demand. From an energy point of view, in a lot of specific application the marginal role of the CHP unit is clearly evident.

The topic of increasing the share of CHP generation in district heating systems is highly relevant. Considering the above exposed problems but knowing the real beneficial effect of the promotion of CHP plants for energy saving policies, the aim of the present paper is to propose some different point of view in order to appreciate the benefit of CHP technology both for industrial and civil sector. The definition of optimal strategies both for the design of the system and for the operation is proposed. A test case is used in order to analyse the differences between current results and optimized results. Finally, some proposal for the definition of tools for optimum design of CHP, considering operational objectives, and for the definition of future economic support policies of CHP-DHN plants, based on the use of some composed indicators, is discussed and analysed.

The paper is structured as follows: after an analysis of the state of the art of the support mechanisms for promotion of CHP plants and the recent evolution of the installation, in section 3 the authors discuss about a methodological instrument for a correct analysis of CHP plants and propose the use of some different energy-based synthetic indicators that can support both the design of the plant and the definition of a correct operational strategy.

In the sections 4 and 5, the use of the various available indicators is discussed and tested with reference to a specific case and a final discussion about the possible impact of the methodology both on design and definition of operational strategy of CHP plants is provided.

2. Effects of support mechanisms for CHP plants and recent developments

Since the European Directive 2004/8/EC concerning the promotion of cogeneration, the principles on which the EU member states can encourage combined heat and power generation (CHP), both in industrial and in civil sector, have been established. The implementation of these principles in national laws has been uneven and resulted in the adoption of the different support mechanisms shown in Table 1.

In Italy, since 2005, a support mechanism based on the certification of achieved energy savings has been introduced to support energy efficiency measures like CHP plants. This kind of support mechanism is called “Certificati Bianchi” (“White certificates”). The quantification of the benefits related to the use of CHP power plants can be connected in particular with the use of a specific indicator, the PES (primary energy savings), which quantifies the difference between primary energy demand for separate generation of power and heat and primary energy demand for the combined generation (CHP) of the same amount of energy. CHP plants also have the possibility to access the tax exemption for the used fossil fuel, a reduction in excise duties for industrial or civil use, based on the amount of electricity generated.

The effects produced by these 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 [13] and concerning the effectiveness in applying new technologies such as fuel cells [14] or the diversification of investments between the different states of Europe [15]. Some effects were positive as the system spread, optimization and cost reduction. Other effects were “distorted” because of the predominance of the economic on the energetic purpose: oversizing, downsizing and “general condition” sizing. A summary of the negative effects determined by the support mechanisms for CHP promotion is shown in Fig. 1.

In this context, according to Eurostat data [16], the cogeneration market stagnated at EU level in terms of both the cumulative capacity and output (Fig. 2). While installed electrical capacity increased slightly from 111.4 GW to 113.0 GW, the amount of cogenerated electricity decreased marginally from 387 to 382 TWh between 2012 and 2013.

CHP electricity production significantly increased between 2012 and 2013 in Denmark, Bulgaria, Italy, Latvia and Portugal, while substantial reductions were reported in Spain, France, the

United Kingdom, Hungary, Croatia and Greece. European CHP's medium share in gross electricity production remained unchanged between 2012 and 2013 at 11.7%, although it varies significantly between different countries, as shown in Fig. 3. With regard to the heat part of the CHP market, there was a drop in heat capacity and more substantially in heat output (Fig. 4). CHP heat production significantly increased between 2012 and 2013 in Latvia and Sweden, even if a significant reduction was reported in Spain, Germany, France and Austria.

3. CHP plants for residential district heating systems

CHP plants are particularly profitable in the industrial sector but they are also suitable for applications in the civil/residential sector. As the energy consumption in the residential and commercial sector is about 40% of the total, this sector represents an attractive target for CHP applications. In particular, CHP plants can be easily integrated into the already existing gas and electric grids, with the specific objectives of reducing peak demands of electric power, and mitigating transmission and distribution congestion [17].

The first level of application is represented by micro-CHP for single house service. A typical micro-CHP system has a quite high electrical efficiency, in some cases above 50%, and an overall efficiency of above 80%: thus providing an example of highly competitive and sustainable technology. In this context, several authors in the literature have shown that gas applications (including small micro-cogeneration and hybrid heat-pump systems) and the gas infrastructure can play an essential role in smart grids, and represent a cost-efficient cornerstone in balancing our networks when intermittent renewable energy sources are deployed on a large-scale [18, 19].

However, these potential benefits can be fully achieved only if accurate methods to forecast thermal and electrical production are developed, together with coupled plants operating at the same ratio of heat and electricity demand. This is a very challenging task, as the required proportion of thermal, electrical and heating requirements depends on geographical and time scales. See for instance Fig. 5, for the case of an 80 m^2 single-family household, with an average number of occupants in the case of typical Northern Europe (N_EU) and Southern Europe (S_EU) environmental conditions respectively (cooling was not considered for simplicity). Fig. 5 was depicted by using climatic data of Copenhagen (N_EU) and Pisa (S_EU), available from RETScreen. Note that the time-varying energy demand poses challenging control issues [20].

Considering plants of different size, cogeneration plants are also particularly suitable for applications in the sector of residential district heating networks (CHP-DH) in order to attain remarkable energetic, economic and environmental benefits. Several studies in the scientific literature have focused on the exploitation potential of the thermal power plants waste heat [21]. However, even though the combined generation of heat and power is highly efficient, it is necessary to have an adequate level of heat demand close to the plant site.

Data of Fig. 5 show that a remarkable problem in the design of CHP is really the definition of a correct size of the plant, in particular of the CHP unit. It is clear that the remarkable variation in the thermal load does not permit of satisfying the thermal requirements only with the CHP plant; a conventional auxiliary boiler is quite always necessary in order to support the operation of CHP system. However, the CHP size should be as large as possible, while the conventional boiler must be of reduced size.

Many efforts have to be done in urban areas in order to promote the adoption of distributed generation systems and in particular to install CHP technologies and district heating systems [22].

3.1 Design of CHP plants and methodological instruments to support the correct sizing

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. They depend 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. This coefficient defines the ratio of the maximum heat flux from the CHP to the maximum demand for heat. 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. Therefore, the search for a well defined methodology for an optimum design is not easy.

In the recent literature, there are different papers in which the topic is to define an optimization model for the design and the operation of a combined heat and power distributed generation system in urban area context as [23].

Due to the technical and economic limitations, and the several parameters that affect the operation and economy of the system, the capacity of a CHP unit is actually based on a case by case optimization, rather than the adoption of any rule of thumb. Various optimization criteria have been suggested to this aim, like the mean annual gain [24].

The analysis of the literature clearly highlights the complexity of planning new systems and evaluating different ways of operation basing on the utilization of the typical performance indicators.

The design of CHP plants depends on many variables, which have not all the same incidence. It can be implemented in three steps, increasingly detailed, as illustrated in the diagram in Fig. 6. The last one is the most important and complex because the thermal load of a CHP plant, meeting the needs of residential consumers, could be characterized by a large degree of irregularity.

Considering the specific operation of CHP power plants and the variable load requirements linked to the civil sector, a real problem in the design of a CHP plant is the definition of the size and a correct matching of all the components. However, the subject of optimal operation of district energy systems has a huge economical potential.

Due to the complexity and the large number of options and parameters available for such kind of plants, finding optimized solutions for system synthesis, design, and operation is a very difficult task. Most of the scientific literature always highlights the problem of “optimal design” of the systems and criteria or objective functions to be considered in order to pursue the objective of energy efficiency and economic value: the interrelation among thermodynamic, economic and environmental approaches is particularly important for the synthetic design and for the optimisation of advanced energy systems, where operating parameters are taken into consideration, and also for comparative analysis. Other possible performance indicators for a CHP plant can be extracted from the EU regulations. In order to understand the definition of these indicators, described in Table 2, a conceptual diagram is shown in Fig. 7.

The performance indicators referred in Table 2, of common use for the analysis of CHP systems, give surely a first element for the evaluation of a CHP installation, but they surely suffer from some methodological limitations mainly when systems of different dimensions are compared.

Analyzing the third indicator, for example, its use clearly favourites the design of CHP of reduced size and high size boiler, because it is an indicator substantially based on the First Law Efficiency.

The analysis of complex plants like CHP based on the use of a single indicator among those described in Table 2 leads to some questionable conclusions even if each of them has some important peculiarities. Obtaining a clear indication about the real performance of a system using a single indicator is difficult but, unfortunately, in a lot of countries the financial support policies are often based on the uncritical application of some indicators.

Therefore, it is possible to frequently observe downsizing of the CHP plant and systems operating with quite low efficiencies (the share of operation of the auxiliary boilers is quite high). In this way, the potential of CHP systems for energy saving is not fully exploited.

Considering that in a lot of engineering design problems the optimum design is the best compromise among different objectives and that, for this reason, a lot of optimum design approaches evolved from single to multi-criteria, an optimal operating strategy based on multi-objective functions is surely more appropriate.

The most remarkable approaches were based on the Laws of Thermodynamics (first and/or second law efficiencies), introducing the concept of minimizing the exergy losses connected to the operation of an energy system: in this way, considering well defined laws for the thermal and electrical load, the optimal system is the one that minimizes the exergy losses and increases the size of CHP with respect to the auxiliary boiler. However, such a kind of analysis takes into account only the energetic elements without considering the economic aspects connected to the components and the energy prices.

In recent times, attempts to add specific cost of the energy produced ("thermoeconomic") and emissions to the atmosphere ("environomic") were made considering the aggregation of the different dimensions (thermodynamic, economic and environmental) in a single objective function defining the total cost of the system operation.

Considering the system composed by a different number of units (CHP plant, auxiliary boilers, heat exchangers, etc.) and capable of producing different services (heat and electricity), the optimum can be referred to the minimum value of the total cost of the system, defined as follows:

$$K = \sum_r Z_r + \sum_r \sum_k K_{ok,r} + \sum_e K_e - \sum_r K_{ro} \qquad (1)$$

where Z_r is the capital cost related to the r-th unit of the system, including charges and maintenance cost, $K_{ok,r}$ is the cost of resource and services, K_{ro} is the revenue from products or services that the system provides (energy, steam, hot water etc.) and K_e is the generic environmental cost. This last term, in particular, distinguishes the "environomic" from the "thermoeconomic" perspective.

Using a function expressed in the terms described by Eq. (1) as objective function, the optimal system is the one that minimizes the cost function during a well defined temporal basis (for example one year of operation).

The choice of the systems can be based on a case by case optimization, despite several attempts have been carried out basing on general criteria such as the annual average gain [25], the determination of hourly trend of the daily thermal load [26], environmental performances [27] or a compromise between some of them according to a multi-objective approach [28].

The uncertainty in some of these factors, for example the evolution of prices and the relevant variations of loads, introduces additional difficulties in the definition of well defined design conditions and, consequently, in the development of a unique methodology of CHP plant design [29].

All the new approaches can be reconnected to multi-objective optimisation but their application requires a careful analysis of the problem considered and the aggregation of different indicators into a common basis. The optimal system is the one that maximises or minimises a particular utility function expressed in the generic form by the following equation

$$U = \sum_{i=1}^{k} U_i = \sum_{i=1}^{k} w_i f_i(x) \qquad (2)$$

where w_i is a scalar weighting factor and $f_i(x)$ is a specific indicator (for example the four indicators defined in Table 2) expressed in dimensionless form. In this way it is possible to consider in the same time different objectives or objectives with different metrics.

To really appreciate the beneficial value of CHP power plants installation, an important performance indicator, which has to be introduced in all the evaluations, is the exergy losses. A good way for considering exergy losses is the use of a simple indicator or objective function capable of conjugating "energy efficiency" and reduction of pollutants at micro-level with energy conservation at macro-level, considering energy consumption terms too.

A synthetic indicator that can provide a comparison between plants using different fuels can be carried out making reference to the maximisation of a function [30] that aggregates the three main elements involved in the analysis as follows:

$$\Psi = W_{out} - \sum_k I_k - \gamma Q_{in} \qquad (3)$$

where W_{out} is the output power, I_k is the exergy loss related to the k-th part of the system, Q_{in} is the energy consumption and γ gives a measure of the input energy with respect to the output energy. The parameter γ may assume any possible value between zero and an upper bound level. More properly, this coefficient accounts the physical characteristics of the input fuel and the current technological status of energy conversion systems. The higher γ the higher the quality of the fuel used and a more advanced technology should be used to convert it. In general, a possible value of γ is the average efficiency of the plants used to convert a type of fuel.

The use of the parameter γ permits to introduce the weight of the energy input, making possible to define a grade for the fuel and extend the analysis to systems with two or more different energy inputs.

The term ‘‘cogeneration’’ is traditionally used with reference to the combined production of heat and electricity from fossil fuels. However, in recent years, the opportunity to develop hybrid systems, in which traditional and renewable energy sources are integrated, is gaining more and more consideration. Other types of cogeneration sources can be adopted, in primis from solar power that allows for clean high-performance solutions. For this reason, in order to take into account this difference, the indicator defined with Eq. (3) can be modified as:

$$\Psi' = W_{out} - \sum_k I_k - \gamma Q_{in} - \gamma^* Q_{in}^* \tag{4}$$

in which the last term considers the input energy from renewable energy sources. A similar idea can be applied to the analysis of energy systems with two or more different outputs so that the indicator defined can be the following:

$$\Psi'' = W_{out} - \sum_k I_k - \gamma Q_{in} + \varepsilon Q_{out} \tag{5}$$

where Q_{out} is the heat output and ε is a quality index of the energy output which can differentiate the heat produced basing on a quantitative index (temperature, steam quality, etc.) [31]. This last objective function can be considered appropriate for plants in which a CHP section is present.

3.2 Definition of the optimal operation and management strategy of the CHP based on the use of composite indicators

In the major part of the technical applications of CHP-DHN, at least one cogeneration unit (internal combustion engines, gas turbines, steam turbines, fuel cell, etc.) supports the base load, in the most efficient way. The CHP unit is assisted by one or more integration or backup systems (boilers, heat pumps, etc.) in order to cover peak loads or unexpected malfunctions in the main unit. Sometimes, the network also includes storage units used to meet peak demand and to ensure a smoother functioning of the plants. The operational strategy of the plant is primarily important in order to optimize energy consumption: it can run in a continuous way (24 hours for day and 7 days for week) or it could be turned off at certain hours to allow fuel savings.

Usually, plants can be managed to meet the electricity demand, integrating with an auxiliary heat source, or to meet the thermal demand, using the network as a “virtual-storage” where to feed-in electricity when demand is lower than the production or get it in the reverse situation.

The choice of a particular type of strategy varies also according to the plant purpose and current political-economic context (possibility to feed into the grid, electricity sales remuneration, etc.). Management must take into account the operation of the various components of the system.

Any thermal or electric generator loses efficiency points working far from its rated power. In the absence of a correctly sized thermal storage system and in the presence of strongly varying loads, the frequent problem is to force the integration units to operate really far from the design conditions: such systems are forced to turn on/off continuously to follow user load that oscillates rapidly. In this way, the system works in continuous transient conditions, with an overall efficiency that is reduced considerably, and with very high response times due to the system inertia. A summary of the factors that influence the operational strategy is shown in Fig. 8.

Considering the methodologies for design and management of CHP plants, the issue of the energy based optimization not always matches those concerning the economic point of view. In particular the economic optimization is linked to incentive systems occurred over the years that caused some situations in which financial support has been established for not correct sized and optimized systems. In general, the higher the number of equivalent hours of operation of the CHP plants, the greater primary energy savings and the reduction of pollutant emissions; however, the cost of fuel can have an economic weight as to lead to higher overall costs than a less efficient management, with equally satisfied heat requirements. Therefore, considering a more general point of view, two possible optimization strategies can be pursued in the design of a CHP plant:

1) to set up an optimized operational strategy for an existing configuration;
2) to consider optimal sizing and optimal operational strategy for well known load data.

4. Analysis of a specific case study

In order to better explain the problems connected with the operation of CHP plants and to carry out possible optimum design strategies for the system management, a test case is considered in the present section. The analysis of the test case is important both to better understand the problems connected with the development of the CHP plants both for what concerns a correct definition of the size and an optimal management strategy. In this case, the sizes of the components are already defined and the analysis is limited to the definition of the optimal operating strategy of the systems, considering a variation of the share of CHP operation with respect to the conventional applied strategy.

4.1 Description of the CHP system

The authors have used the data acquired on a real available plant that can be considered representative of such a kind of systems. The CHP-DHN under study is located in a town located in the north of Italy. 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);
- a seminar room (volume of 2400 m^3).

The total heat demand peak is about 2500 kW_{th}. The hot water produced by the system is used both for sanitary and heating purposes. The electric power installed in the complex is about 2700 kW (about 300 kW for the service building and 200 kW for the conference room).

In the current configuration, the thermal power is generated by a CHP based on an internal combustion engine with natural gas as fuel: the electrical and thermal nominal powers are 970 kW_{el} and 1160 kW_{th} respectively. In support of the CHP unit, in order to follow the variation in heat demand, three natural gas-fired boilers are installed: a condensing boiler of nominal power 900 kW_{th} and two conventional auxiliary boilers with a nominal power of 2600 kW_{th} each (the second is only installed for safety reasons). Even if the maximum power required is 2500 kW_{th}, the maximum available thermal power is about 7250 $kW_{th.}$

The heat distribution system is characterized by pressurized water. In nominal conditions the following data can be considered: pressure at 4.5 bar with return at 4 bar and inlet flow temperature at 75 °C with return at 62 °C, but obviously during the real operating conditions the flow temperature increases and the return temperature decreases. A simplified schematization of the plant is provided in Fig. 9. The current management strategy of the plant implies that the CHP follows an electrical predefined profile, while thermal integration systems cover the remaining heat demand, following a preset supply temperature of the distribution network, as shown in Table 3. The system under analysis is described in detail in [32, 33].

The distribution network is branched/meshed direct type without exchange substations. The network consists of a double pipe (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 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 Acquisition and analysis of plant data

The remote monitoring system allowed studying the dynamic behaviour of the system during the whole heating season: from 15 October 2015 until 15 April 2016 (operating period of the heating systems, according to Italian regulations for the northern Italy). Due to a technical fault, the CHP unit has worked, according to the project specifications, only for the month of December, which can be considered significant for the whole heating season. For this period, the data listed in Table 4 has been analyzed in detail. The average thermal load profiles have been deducted by the energy progressive consumption recorded by meters for each i-th time instant, by calculating the ratio of the energy variation ΔE measured in each i-th time interval and the interval itself and defining an average value of the thermal power:

$$\bar{E}_{th} = \frac{\Delta E(\Delta t_i)}{\Delta t_i} \tag{6}$$

The sampling frequency, with which to acquire data from the monitoring system, has been carefully chosen to avoid introducing errors due to the technical specifications of the meters: the comparison has been made between average values of the measurements obtained considering one hour or fifteen minutes. The results show that the technical specifications of the installed equipment on the users strongly influence the choice: the counters have a resolution of 10 kWh that correspond respectively to 10 kW_{th} and 40 kW_{th} power leap on load profiles calculated by consumption, as clearly shown in Fig. 10 and Fig. 11. The second power leap has not been considered acceptable because the majority of the loads have an average value of 40 kW_{th} and, therefore, one-hour interval has been chosen as time step for the acquisition of the data.

As already mentioned, the measurement equipment is not installed for in-depth analysis but only for consumption accounting. This is the reason for the absence of meters on the secondary side of the heat exchangers that would allow the evaluation of their efficiencies and that of the distribution network. The “a-posteriori” installation of external meters showed evident limitations in obtaining a sufficient degree of accuracy for this type of application.

4.3 Management issues and optimized scenario

Taking advantage on the economic support policy, a plant like the one described in section 4.1 can benefit the incentives for high efficiency cogeneration linked to district heating systems.

Currently, the operator can still access the fuel tax exemption for industrial uses, according to the Italian regulations, being a cogeneration system for civil use in which the electricity produced exceeds 10% of the thermal energy required. This constraint determines a sizing of the CHP plants at quite reduced values.

The CHP unit does not operate at its full potential but mainly to cover the electrical self-consumption of the offices because the return from electricity sale is very low. According to the scheduling described in Table 3, it works in the range between 72 to 87% of its capacity when it is on. In this system, like in a lot of other systems, most of the thermal demand is met by the integration systems (conventional boiler) as described in section 4.1.

Such management strategy does not follow the purposes of the CHP application in district heating systems because it does not take full advantage of the technology to reduce primary energy consumption and polluting emissions. Another issue that complicates the system management also lies in the sizing of power generation systems: boilers are significantly oversized and they are often forced to work at a quite low load because of the large fluctuations in the heat demand.

From an energy point of view, in Table 5, the distribution of heat load between the components of the thermal power plant clearly shows the marginal role of the CHP unit in such management.

Using a dynamic simulation model (a fixed-step time-series model) developed using a Matlab-Simulink platform and validated using the experimental data obtained with the current network management, a different scenario has been simulated. An improvement to this approach could be given by a transient investigation of the considered CHP system but, at this step, the authors want only to prove the possibility of justifying the increase of the operating share of a CHP during a meaningful operating time.

In the simulation, the CHP unit is set to thermal tracking and boilers work only to cover the daily peak load, with priority for the condensing boiler rather than the traditional one. The setting is still carried on the network supply temperature to ensure the right comfort to the users. With this type of management, the traditional boiler has an insignificant role in satisfying the heat needs. The CHP unit works at its power peak except when the load request is less than its rated thermal power (at night) or when the condensing boiler can not modulate lower. From an energy point of view, the distribution of the thermal load on the thermal power plant components varies in a meaningful way: most of the requirements are met by waste heat from the CHP unit (see Table 5). Consequently in the optimized scenario in which the operation of the CHP unit is maximized, the request of total primary energy and the production of electric energy increases, as shown in Fig. 12(a) and Fig. 12(b).

The data contained in Table 5 and Fig. 12 show that, in an optimized management scenario, the share of operation of the CHP plant can increase from 29% to 79% and the operation of the boiler can be drastically reduced.

Moreover the operation of the second boiler (conventional) is not necessary because it could be theoretically required only for the 0.1% of the total heating period (a very low number of hours). So only the condensing boiler is necessary and only a single (safety) conventional boiler can be maintained.

4.4 Economic analysis

To get a full view of the real convenience of one management rather than the other, it would be necessary to check the behaviour of the plant for an entire year. Considering the available operating data, the analysis is limited to the month of December. Only the components of costs and incomes that actually differ between the two types of configurations have been examined:

- purchase cost of natural gas (estimated in 0,4127 €/Sm^3);
- maintenance costs of the CHP (dependent on working hours and estimated in 10 €/h);
- incomes from the sale of electricity to the national grid (ranging from 0.084 €/kWh to 0.1042 €/kWh).

The calculation, in Table 6, was made taking into account the different components of italian taxation, national and regional. Moreover the fuel volume consumed was calculated using a standard calorific value (34.53 MJ/Sm^3). As evident, the increased purchase of natural gas nullifies the effort to manage the CHP plant in such a way to optimize the primary energy exploitation. Even if this kind of estimation is really dependent on monthly changes in electric energy prices and, above all, the purchase cost of the primary resource, from a purely economic perspective, the optimized operation strategy appears to be not particularly meaningful.

4.5 Evaluation of the performance of the system based on the use of conventional indicators of performance

This section focuses on two types of approaches for the performance indicators described in section 3.1: a conventional and a “dynamic” approach, as provided in Fig. 13.

The conventional application on a monthly balance shows the results summarized in Table 7. Such an approach appears very limited in providing information on the dynamic behaviour of the system: the civil/residential load of the district heating systems is characterized by high fluctuations during the day that force the plant to work in continuous transient conditions. Therefore, the application of an indicator for very long time intervals can provide distorted information about the operation of the plant.

The dynamic analysis of the same performance indicators has been carried out with the objective to explore the possibility of obtaining useful information for the design and optimization of district heating system management, observing their trends on increasing time intervals, from fifteen minutes up to a day.

The fundamental problem of this type of approach is to establish a time base on which to calculate the indicators that does not influence the results. Attempts over shorter intervals showed evident limitations in the possibility of obtaining correct information: in many cases, the inertia phase shift between the numerator and the denominator generated abnormal trends. "Cleaner" profiles have been obtained calculating the same parameters for longer time intervals (three, six, twelve hours and one day).

As was expected, in both configurations (Fig. 14 and Fig. 15), the *PEF* trend oscillates between two values: the higher one during the ignition periods of boilers and the lower one during the hours in which the CHP plant operates. A similar situation can be observed considering the third indicator *PEE*.

Fig. 16 provides the trend of the efficiency of the distribution, η_{DH}, in the optimized scenario, showing how it is quite stable (this is not observed in the current management scenario) and clearly it follows the temperature profile: obviously, thermal losses depend on it.

In the case of more complex systems, such as hybrid systems or in the presence of renewable resources, the study of the *PEF* profile, in combination with primary energy variable prices, could reveal useful information about the management or about the possible new incentives aimed at forcing the plant owner to make it works most efficiently. The η_{DH} profile may allow the evaluation of thermal stress of the distribution network and provides useful information to the correct sizing of a possible storage volume. The analysis of the system obtained using each one of the different indicators reported in Table 2, considering the two different operating strategies, does not encourage the shift from a conventional operating strategy to the optimized one.

5. Analysis of the case study and use of different performance indicators

The utilization of simple performance indicators like those discussed in Table 2 does not permit a satisfactory comparison of the two different operating strategies. However, from the application of the different indicators described in section 3.1, a composite indicator can be defined, considering the weighted contribution of some of them in a dimensionless form.

According to the description given with Eq. (2), a new utility function U to be maximised can be defined in the generic form as:

$$U = \sum_{i=1}^{N} U_i = \sum_{i=1}^{N} \left(w_i f_i(x) + F_i \right) \tag{7}$$

where $f_i(x)$ is the i-th performance indicator expressed in dimensionless form, w_i is the weighting factor and F_i is a constant dependent on the indicator range.

The weight function w_i and the constant F_i can be defined for example as:

$$w_i = \frac{1}{f_i^{max} - f_i^{min}} \tag{8}$$

$$F_i = -\frac{f_i^{min}}{f_i^{max} - f_i^{min}} \tag{9}$$

where f_i^{max} and f_i^{min} are, respectively, the maximum and minimum value for the i-th indicator.

The definition of these two values depends on the purpose of the utility function: it can be a comparative analysis between different management strategies of the same plant or a design 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 indicator comparing all the analysed configurations.

For the various analyzed configuration, the best one will be the one corresponding to the maximum value of the objective function U.

A composite utility function for a multi-criteria analysis can be obtained considering all the performance indicators analyzed in Table 2. Applying this approach to the case analyzed in section 3, the values shown in Table 8 have been obtained, founding the calculations on some possible reference values from the literature (f_i^{max},f_i^{min}). The resulting composite indicator is negative because of the oversize of the power installed in the system but, anyway, it is evident that the "optimized scenario" gives better results than the "current management".

Such an approach may be useful in the context of incentives for CHP systems to avoid the "distorted" effects described in section 2 because, observing a set of indicators rather than just a single indicator, it is possible to define a more complete analysis of the system and a proper management of any facility. Similar results can be obtained using the dimensional indicators analyzed in Eq. (3)-(5).

Referring to the case study analysed in section 4 and considering the two management scenarios (current and optimized), the composite indicator defined with Eq. (5) has been calculated with reference to both the cases. They are shown in Table 9.

The coefficients defined for the calculation are $\gamma = 0.6$ for natural gas (considering the fact that the best available technology for transforming natural gas into electricity is the combined cycle power plant) and $\varepsilon = 0.2$. The last value is selected because of the low temperature of network supply. In both cases the synthetic indicators defined in section 3 can give a quantitative justification to the optimal design strategy. In particular, it can be shown that the indicator defined by Eq. (5) and analysed in Table 9 can be really suitable for defining guidelines for the size design of a CHP plant. Analysing the data of Table 9, the convenience of an optimized strategy is obvious: in this case the higher fuel consumption can be fully compensated by the increase of the electricity production, maintaining a very similar value of the absolute exergy losses.

6. Conclusions

In the last decades, CHP plants for civil applications have been the subject of several studies in order to promote their diffusion and to develop a general optimization procedure. The issue is still the choice of the size and the operational strategy to cover the overall requested energy (heat and electricity) by consumers, achieving significant primary energy and emissions savings while maximizing plant profitability.

Many efforts have to be done in urban areas in order to promote the utilization of distributed generation systems and in particular to install CHP systems and district heating systems. Especially in small-medium CHP systems, the combined generation occurs at a constant or slightly variable power-to-heat-ratio, while the heating, cooling and electrical demands of the users are independent from each other. In addition, daily and seasonal variations in the electrical and thermal load, economies of scale, various CHP technologies, operational strategies, energy prices, support mechanisms and existing legislative frameworks create further complications, as well as “distorted” effects far from the real purpose of cogeneration.

The paper puts clearly in evidence the problems connected with an efficient use of CHP systems and discusses how the development of methods and indicators, that try to combine the economic benefit and the energetic objective, could be helpful in order to increase the share of CHP generation in district heating systems. These problems have been analysed and discussed, referring to a specific case study. The paper proposes the use of composite indicators based on technical and economic indicators for planning the operation of small-scale CHP units in district heating systems.

Referring to the case study, the analysis of the system, based on the use of all the proposed composite indicators, can justify how to increase in a meaningful way (from 29% to 79% of the thermal energy produced) the share of thermal power produced with CHP reducing as a consequence the operation of the conventional auxiliary boiler.

In the paper, the authors discussed how it could be possible, through the development of some composite indicators (taking into account simultaneously both the economic value of the investment and the energetic objective of increasing the system global efficiency reducing exergy losses), to define guidelines for a correct approach to the design of small-medium size CHP systems. Though if the study is only limited to a quasi-steady analysis of the system, the possibility of justifying the increase of the operating share of a CHP during a meaningful operating time appears evident.

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Tables and captions

Table 1. European support mechanisms for CHP plants

Mechanism	Description
Feed-in tariffs	Feed-in tariffs (FITs) are an energy output-based mechanisms designed to provide direct support for CHP applications. CHP plant operators receive a bonus for each kWh of electricity generated or fed into the grid. In general, the bonus can be fixed, be defined as a share of the electricity price, or be indexed against fuel prices.
Certificate schemes	Certificate schemes are market-based mechanisms that provide additional revenues to the operators of CHP facilities. A state authority places an obligation on electricity suppliers to obtain a certain amount of primary energy savings. An independent certifying body evaluates the actual savings achieved and assigns certificates which can be traded on the market.
Investment support	Investment support is a mechanism aimed to reduce barriers of high up-front investments of CHP plant construction. It is the grant of allowances for the installation of new facilities or the renovation of existing ones, which must meet strict criteria on energy saving and emissions, related to the current technological scenario.
Fiscal support	Fiscal support is a mechanism that has often taken two forms: tax exemption for the used fuels or the generated electricity; accelerated depreciation for new plants. In general, the systems must meet certain performance criteria or a minimum annual usage rate in order to access these benefits.
Beneficial allocation of CO_2 emission permits	The allocation of greenhouse gas emission permits is a "cap and trade" mechanism, applicable exclusively to plants with a thermal capacity of more than 35MW that must participate in the European emissions market. These plants receive an indirect form of support through the allocation of permits according to the single emissions ceiling established at European level.

Table 2. Summary of performance indicators for CHP plants for DH systems

Indicator	Description	Formula
Primary Energy Factor	Theoretical use of primary energy in a cogeneration system for the production of thermal energy only. $f_{P,j}$ is the primary energy conversion factor.	$PEF = \frac{E_{fuel} * f_{P,GN} - E_{el,n} * f_{P,el}}{E_{th,dn}}$
District heating global efficiency	Distribution network efficiency: it defines the ratio between the energy to the end users and the energy produced for district heating network.	$\eta_{DH} = \frac{E_{th,u}}{E_{th,dn}}$
Primary energy efficiency	First law efficiency. $f_{P,j}$ is the primary energy conversion factor.	$PEE = \frac{E_{th,dn} + E_{el,n}}{E_{fuel} * f_{P,GN}}$
Equivalent to nominal power duration	Theoretically number of hours in which the plant works at its rated power (P_{th}).	$h_{eq} = \frac{E_{th,dn}}{P_{th}}$

Table 3. Management logic of power plant components

Component	Management logic	
CHP unit	7:00 to 13:00	850 kW_{el}
	13:00 to 18:00	750 kW_{el}
	18:00 to 22:00	700 kW_{el}
	22:00 to 7:00 from Monday to Saturday and Sunday	Off
Condensing boiler	Supply network $T < 75$ °C	On
	Supply network $T > 77$ °C	Off
Traditional boiler	Supply network $T < 72$ °C	On
	Supply network $T > 77$ °C	Off

Table 4. Available data from the remote monitoring system

Component	Data
CHP unit	Accounted energy, flow rate, flow and return temperature
Primary side of each of the three heat exchangers between thermal plant and district heating network, offices and seminar room	Accounted energy, flow rate, flow and return temperature
Residential users	Accounted energy

Table 5. Thermal load distribution on the thermal power plant components

Component	Current management	Optimized scenario
CHP unit	29%	79%
Condensing boiler	71%	20.9%
Conventional boiler		0.1%

Table 6. Summary costs and income variations between the two management strategies for a typical month during the cold season (december)

Component	Current management	Optimized scenario	Difference
Natural gas purchase	67800 €	82500 €	+ 14700 €
Cogenerator maintenance	4400 €	7400 €	+ 3000 €
Electricity sale	14600 €	33400 €	+ 18800 €

Table 7. Summary of performance indicator results - monthly application

Indicator	Current management	Optimized scenario	Variation	
PEF	0.943	0.533	- 43.53%	Better exploitation of the primary energy source.
η_{DH}	0.95	0.944	- 0.63%	Slight increase of pipe heat loss, related to average higher network flow temperatures.
PEE	0.822	0.847	+ 2.91%	Reduction of thermal power wasted into the atmosphere by the CHP aerothermal dissipater.
h_{eq}	218.3 h	218.3 h	+ 0.0%	Oversizing of the power installed in both cases.

Table 8. Summary of the objective functions for the composite indicator

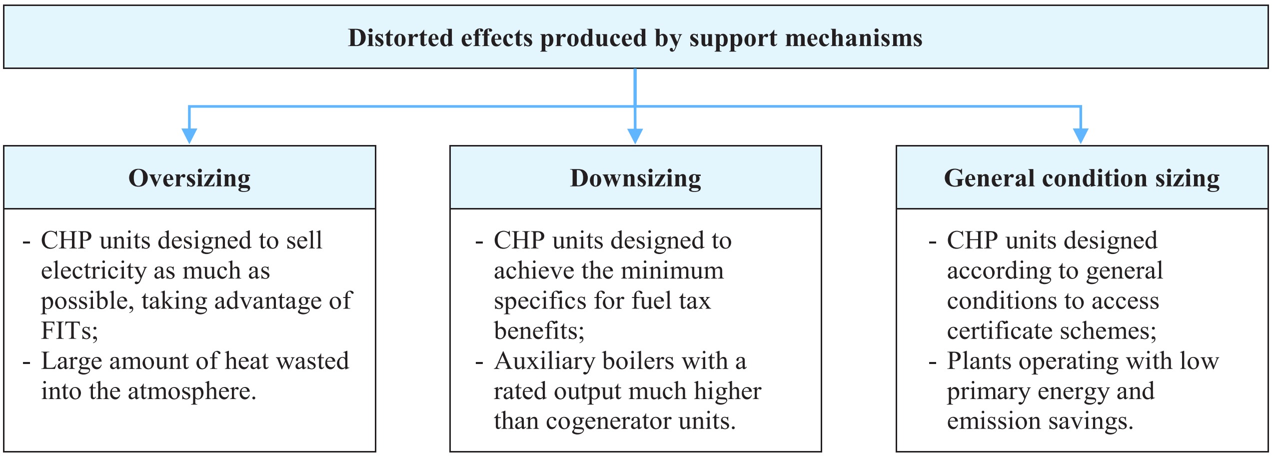
Indicator	Value		f_i^{max}	f_i^{min}	U_i	
	Current management	Optimized scenario			Current management (U = - 0.328)	Optimized scenario (U = 0.206)
PEF	0.943	0.533	0[1]	1[1]	0.057	0.467
η_{DH}	0.95	0.944	0.98	0.84	0.785	0.743
PEE	0.822	0.847	0.95	0.8	0.147	0.313
h_{eq}	218.3	218.3	450	350	-1.317	-1.317

[1] f_i^{max} and f_i^{min} are reversed because PEF is as better as it is lower

Table 9. Summary of the objective functions for the composite indicator

Objective function	Value	
	Current management	Optimized scenario
W_{out}	291.875 MWh	658.995 MWh
$\sum_k I_k$	1146.280 MWh	1143.030 MWh
Q_{in}	1593.870 MWh	1958.605 MWh
Q_{out}	1048.520 MWh	1054.370 MWh

Figures and captions



Distorted effects produced by support mechanisms

Oversizing

- CHP units designed to sell electricity as much as possible, taking advantage of FITs;
- Large amount of heat wasted into the atmosphere.

Downsizing

- CHP units designed to achieve the minimum specifics for fuel tax benefits;
- Auxiliary boilers with a rated output much higher than cogenerator units.

General condition sizing

- CHP units designed according to general conditions to access certificate schemes;
- Plants operating with low primary energy and emission savings.

Fig. 1. Effects produced by financial support mechanisms for CHP plants

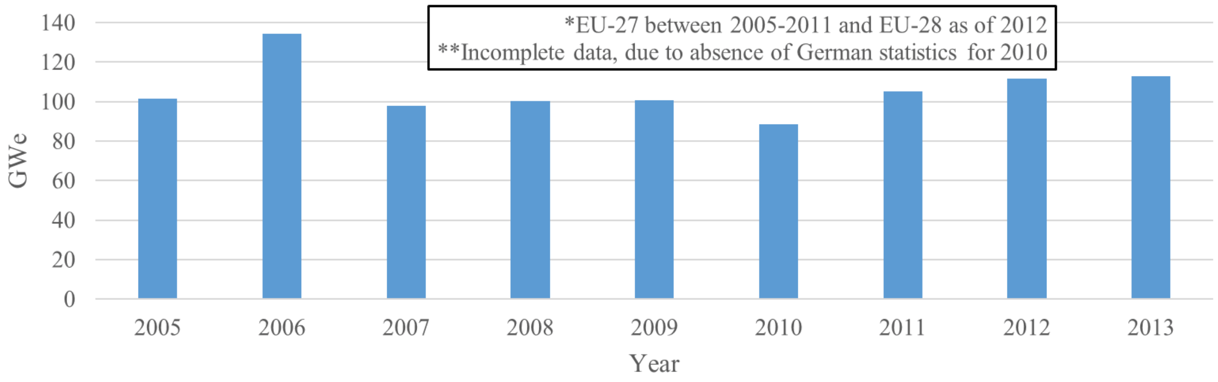


Fig. 2. CHP installed electrical capacity in EU (2005-2013) [13]

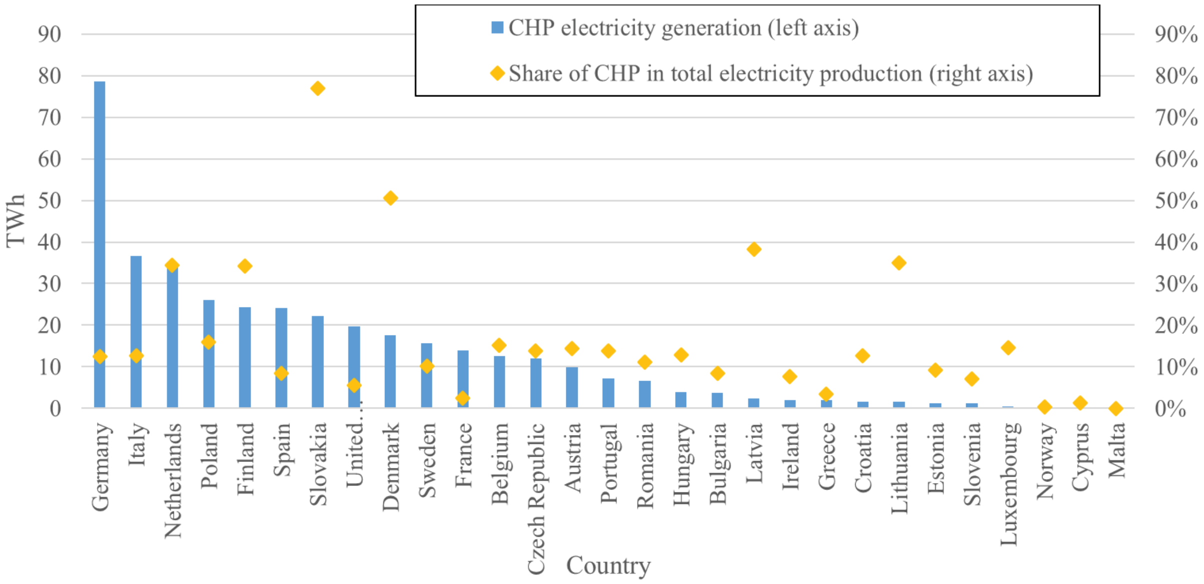


Fig. 3. Cogenerated electricity and share in total electricity production by country in 2013 [13]

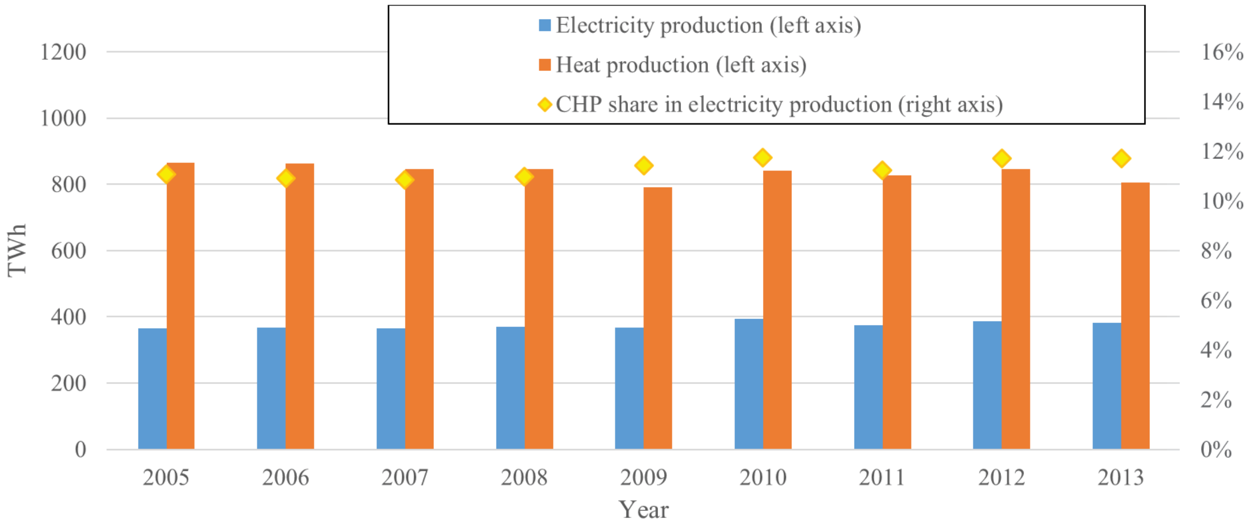


Fig. 4. Generated electricity and heat in CHP plants (2005-2013) [13]

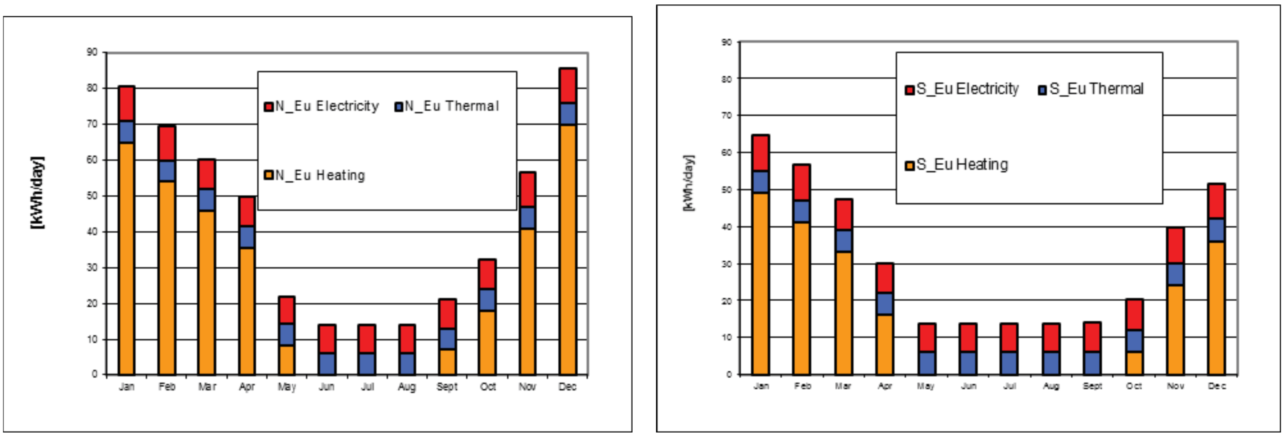


Fig. 5. Typical energy requirements for residential sector in Northern (a) and Southern (b) Europe.

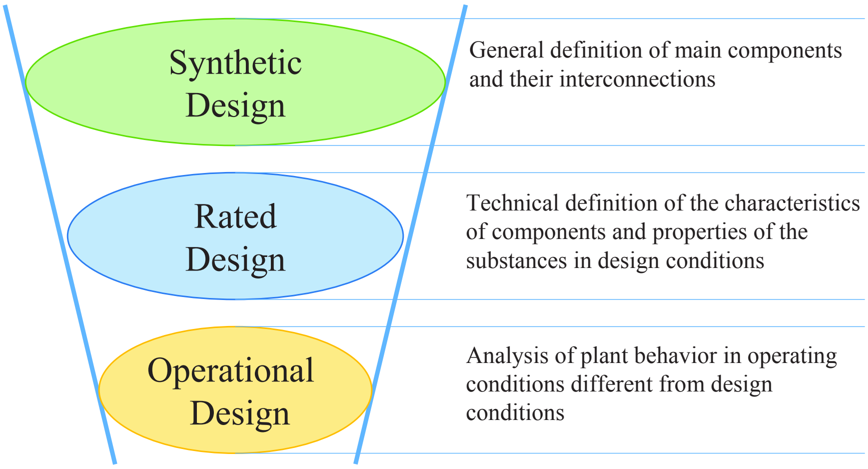


Fig. 6. The different steps of the design

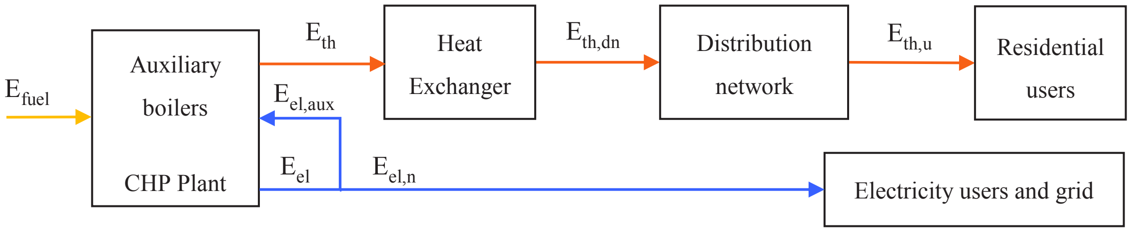


Fig. 7. Conceptual scheme of a CHP plant for the application of performance indicators

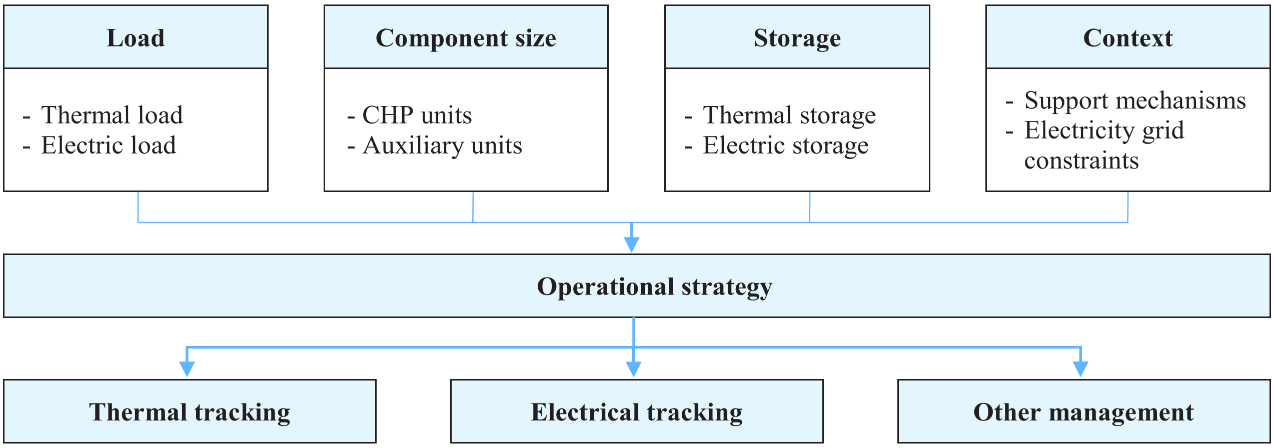


Fig. 8. Summary diagram of the operational strategy

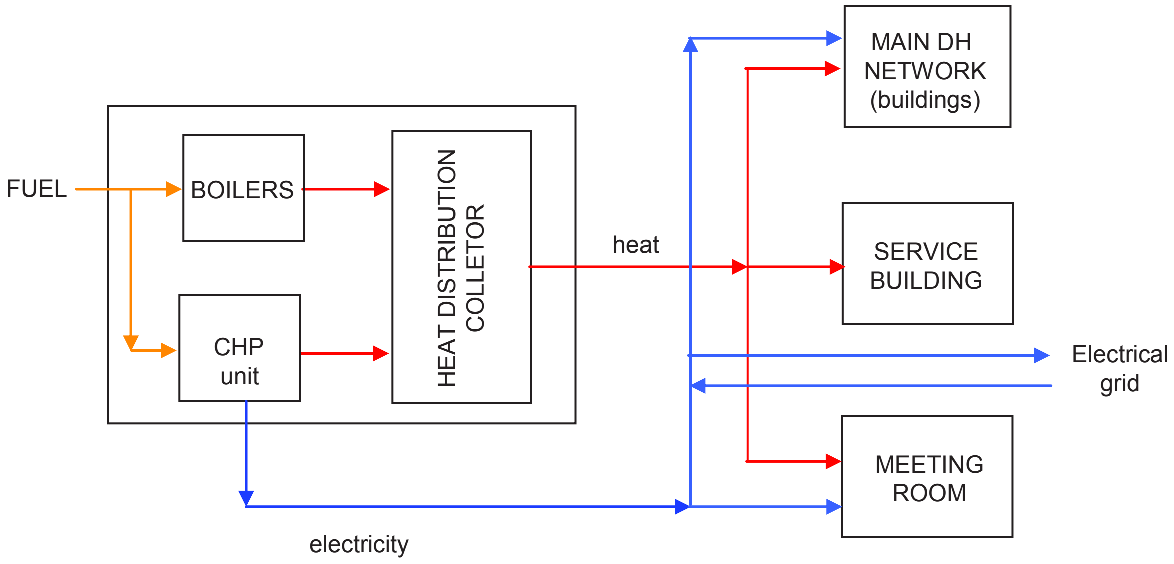


Fig. 9. Scheme of the system under analysis

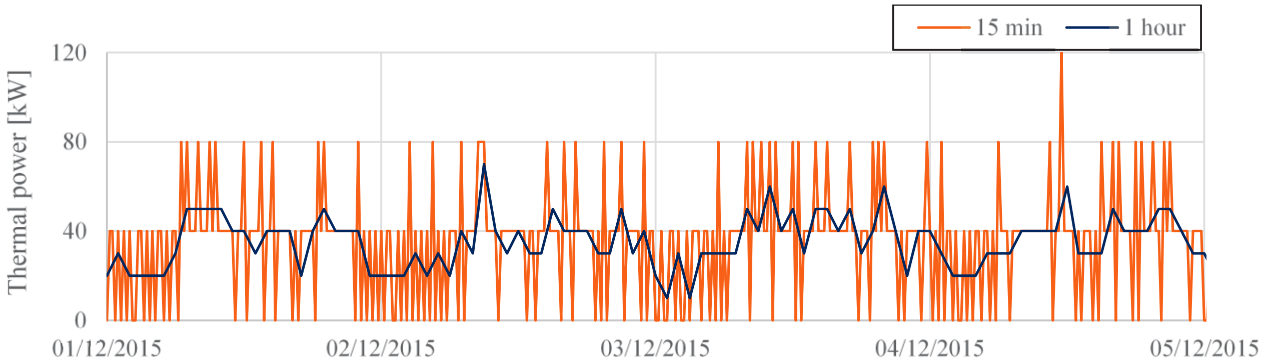


Fig. 10. Example of thermal power profile for direct connected residential building

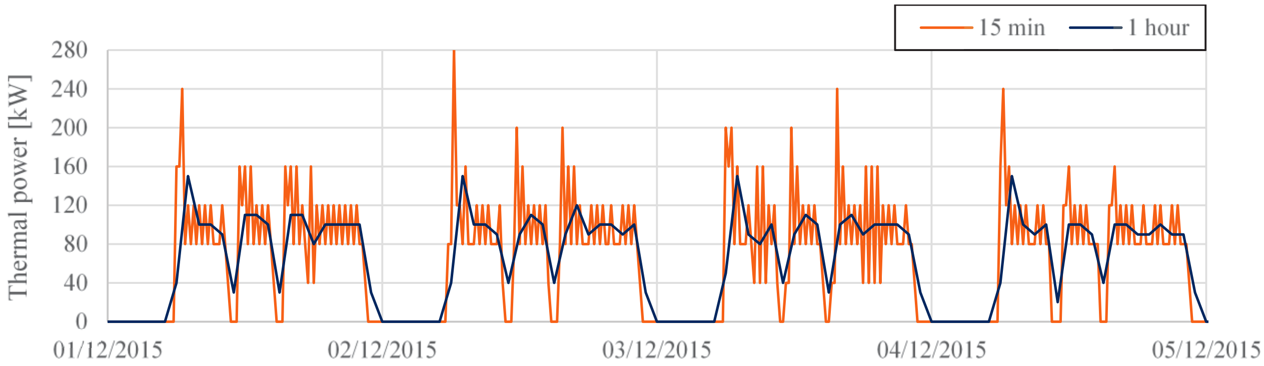


Fig. 11. Example of thermal power profile for indirect connected residential building

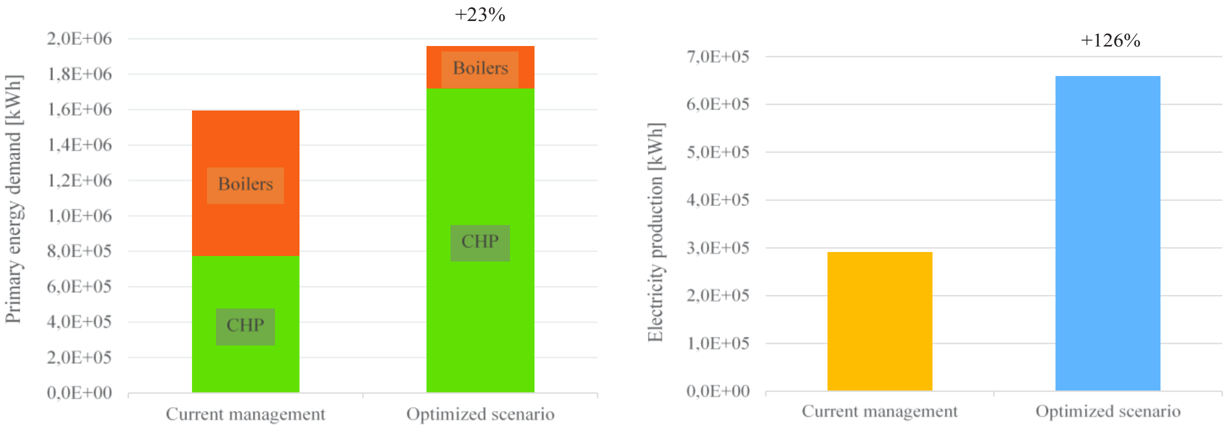
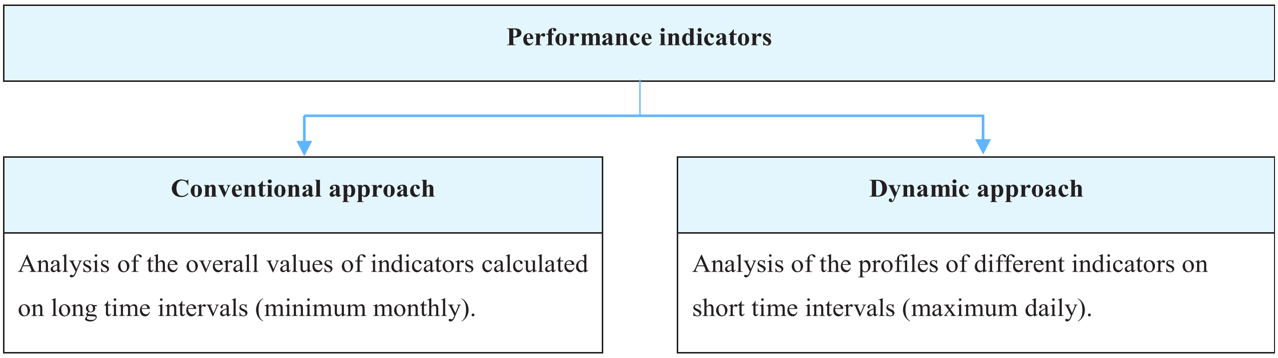


Fig. 12. Difference between current and optimized scenario. (a) Variation and sharing of primary energy demand and (b) Variation in electricity production



Analysis of the overall values of indicators calculated on long time intervals (minimum monthly).

Analysis of the profiles of different indicators on short time intervals (maximum daily).

Fig. 13. Approaches for the test of performance indicators

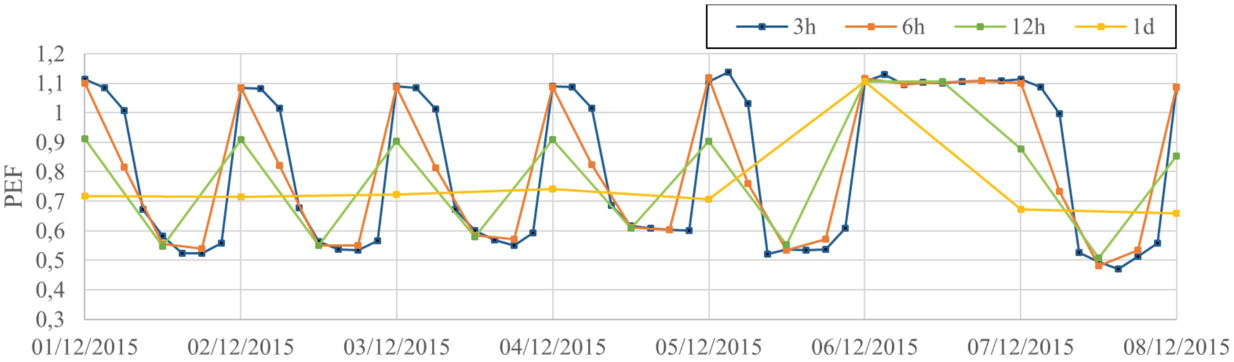


Fig. 14. Measured values of PEF (time interval of 3, 6, 12 hours and 1 day): current management

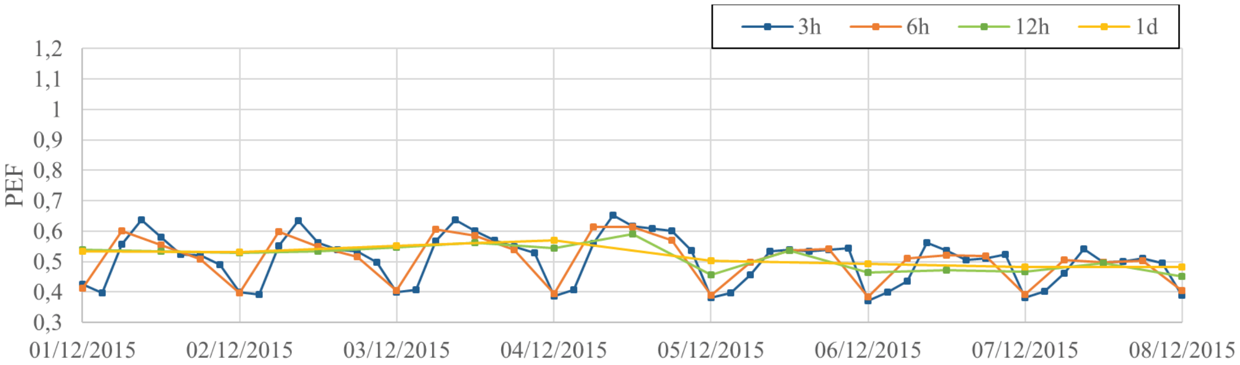


Fig. 15. Estimated values of PEF (time interval of 3, 6, 12 hours and 1 day): optimized scenario

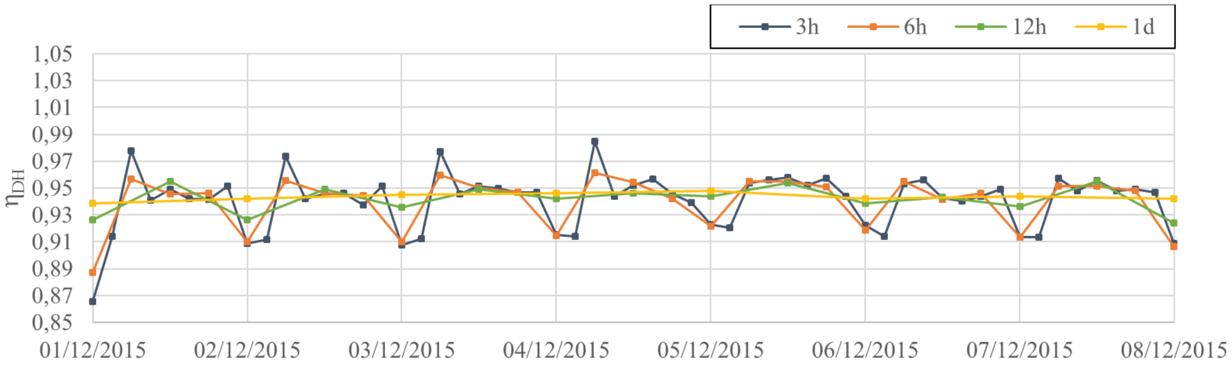


Fig. 16. Estimated values of η_{DH} (time interval of 3, 6, 12 hours and 1 day): optimized scenario