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Optimum sizing of cogeneration plants by means of a genetic algorithm optimization: A case study

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ABSTRACT

In the context of increasing energy consumption, multi-generation systems such as combined heat and power generation (CHP) are attractive to meet the increasingly stringent requirements regarding energy saving in buildings. Hospitals are great consumers of energy, both electrical and thermal: the use of heating and cooling equipment for maintaining satisfactory comfort and indoor air quality for the patients as well as the adoption of several electrical health equipment result in the highest energy consumption per unit floor area of the entire building sector.

In the present study, co/tri-generation systems' optimal set-up, size and operation are investigated for small/medium size hospital facilities. More specifically, after the presentation of the energy consumption profiles for a medium size hospital with 600 beds, set as reference case for this study, a parametric analysis has been carried out varying the peak loads of the user. For each of the proposed scenarios, the optimal plant configuration (sizing of all the energy production systems) has been outlined by means of a numerical code (Trigen 3.0) in-house developed. Afterwards, in order to optimize the load distribution in a smart grid characterized by electrical, thermal, cooling and fuel energy fluxes, an ulterior numerical investigation has been performed. The software, named EGO (Energy Grids Optimizer) consists of a genetic algorithm procedure: it defines the optimal load distribution of a number of energy systems operating into a smart grid based on the minimization of an objective function which expresses the total cost of energy production. Finally, an economic analysis has been carried out in order to evaluate the profitability of the proposed CHP-heat pump scenario.

1. Introduction

The constant trend towards energy efficiency and fossil fuel dependency reduction is a key strategy of European Union (EU) as confirmed by the H2020 goals. In 2014, the overall final energy consumption in EU has become greater than 1000 Mtoe [1]: although Industry, Transport and Household sectors represent about the 84% of total final energy consumption, Services (office, health, wholesale, education, etc.) sector cannot be neglected in order to reduce the total carbon footprint of European Community buildings. Focusing on health sector, it is estimated that in 2015 there were 2.6 million hospital beds available for use across the EU-28 [2] which represent more than 15000 buildings [3]. Moreover, it should be considered that these buildings are, for a large part, quite old and were built without any particular attention to the concept of energy efficiency.

It can be considered that hospitals are characterized by the highest energy consumption per square meter [4]. This is mainly due to

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Nomenclature

C	Cost [€]
L	Load
NPV	Net Present Value [€]
P	Electric Power [kW]
Q	Thermal Power [kW]
ROI	Return On Investment [years]
Acronyms	
AB	Auxiliary Boiler
AC	Absorption Chiller
CC	Compression Chiller
CHP	Combined Heat and Power
COP	Coefficient of Performance
EER	Energy Efficiency Ratio
EGO	Energy Grid Optimizer
EU	European Community
FF	Fitness Function
FFR	Fitness Function Rank
GA	Genetic Algorithm
GT	Gas Turbine
HP	Heat Pump
HVAC	Heating, Ventilation and Air Conditioning
ICE	Internal Combustion Engine
NG	Natural Gas
PM	Prime Mover
RG	Renewable Generator
Greek symbols	
λ	Specific Cost of Fuel [€/kW]
μ	Maintenance Specific Cost [€/kW]
ξ	Specific Cost of Purchased Electricity [€/kW]
Subscripts and Superscripts	
av	average
c	cooling
dis	dissipated
e	electrical
F	fictitious
P	purchase
S	sold
th	thermal

the continuous need of electrical, thermal and cooling energy [5,6]. With more details, thermal energy is required for hot water production, space heating, HVAC (Heating, Ventilation and Air Conditioning) units, sterilization processes, etc. Burned gas in traditional boilers is a high percentage of the total energy consumption in hospitals. In addition, the large volume of the rooms that require to be cooled makes the cooling of these buildings a very energy consuming process [7]. The requirement of electrical energy is very high because of the lighting of big rooms and long corridors, the electrical health equipment, etc.

In this context, the application of a co/tri-generation system can heavily increase the total conversion efficiency for the electrical, thermal and cooling energy production. Indeed, based on the Directive 2004/8 EC of the European Union [8], the development of high efficiency cogeneration is promoted as a viable solution in order to increase the energy efficiency. To this respect, the performance of cogeneration plants become a fundamental aspect: as an example, M. Gambini and M. Vellini [9] carried out an analysis of the Italian context, consisting in the evaluation of the energy performance of the cogeneration units as function of the considered CHP technology and allowing to define useful guidelines for the operators of the cogeneration sector. Similarly, Gvozdenac et al. analyze practical procedures for the virtual recognition of CHP and non-CHP parts of the plant, defining new criteria for the evaluation of high cogeneration performance parameters [10].

On the other hand, the potential advantages to simultaneously meet electrical, thermal and cooling demand [11] are concerned not only in higher final use efficiencies (compared to the separate production) [12,13], with consequent reduction of pollutant and greenhouse gases emissions, but also in promoting the use of alternative technologies such as the absorption chiller [14,15]. A

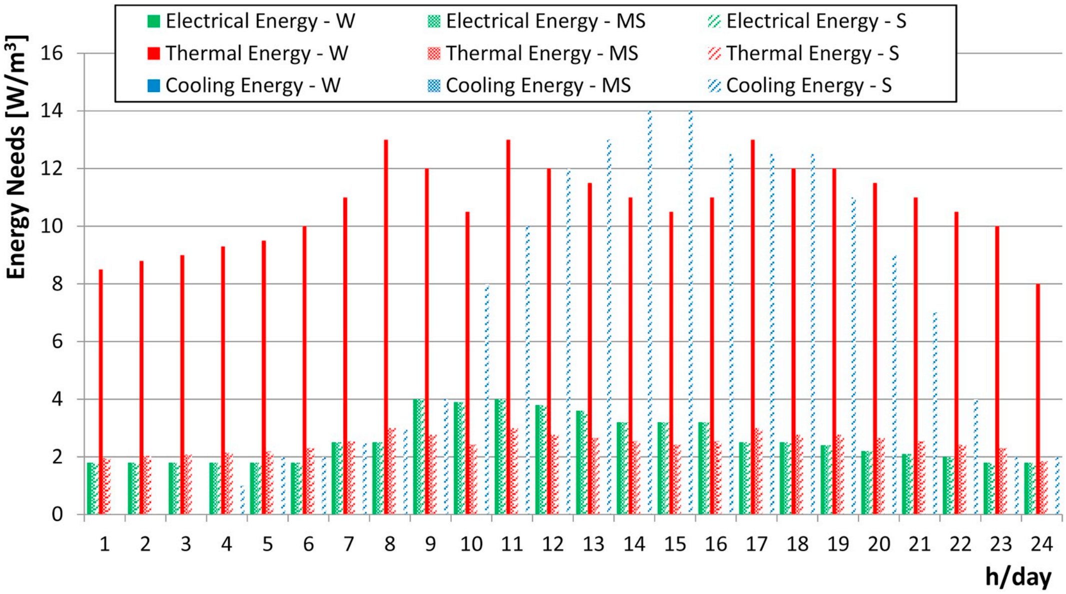

Fig. 1. Energy demand profiles for typical days in wintertime, middle season and summertime.

thermodynamic modeling is carried out in Ref. [16] to compare the advantages and disadvantages of organic Rankine cycle and Kalina cycle as a bottoming cycle for waste heat recovery from a particular cogeneration system named CGAM, according to the first initials of the participating researchers C. Frangopoulos, G. Tsatsaronis, A Valero and M. von Spakovsky. Briefly, a CGAM cogeneration plant consists of a high temperature gas turbine and an air preheater to use a part of thermal energy of the hot gases leaving the gas turbine as well as a heat recovery steam generator in which the saturated steam is produced. Ref. [17] illustrates a particular case study: the design analysis of a cogeneration plant using the heat recovery of a cement factory. Ref. [18] resumes a parametric analysis conducted in order to optimize the performance of combined cycle. The gain in net efficiency of the cycle proved to be from 15 % to 31 % when the temperature at the inlet of the turbine of topping cycle increases from 1000 K to 1400 K. Moreover, it has been demonstrated that the by-pass valve should be opened for small compression ratio and closed for high value of compression ratio. An experimental platform has been studied in Ref. [19], combining a cogeneration plant, a refrigerating adsorption machine, thermal solar collectors and wooden construction split in two compartments, a cold one conditioned by cooling ceilings and a hot one conditioned by heating floors.

Despite the above mentioned attractive concept behind CHP [20,21], in practice there are a lot of barriers that restrict its application, with the most important one probably being its high cost and the often limited utilization (even in presence of the absorption machine) of the recoverable heat, especially when used in space heating applications. Indeed, CHP units are not always optimally dimensioned, thus affecting their performance and economy. For this reason, the size of the plant should be carefully selected. This task is anyway quite complicated, being dependent on diurnal and seasonal variations of thermal and electrical loads as well as technology options and achievable utilization factor in the context of energy prices, scale economies, financing possibilities and legislative framework. Some studies proposed size optimization methods in household sector [22–24], but the different energy needs profiles may make these methods invalid in hospitals sector. Further the optimal load allocation of the introduced CHP energy systems is a key factor to minimize the fossil fuel consumption and to reduce the total cost of energy production.

For these reasons, the aim of the present paper is to study the criteria to determine the optimal CHP sizing and operating units in hospital facility sector. With this purpose, heat pumps introduction – coupled with CHP systems – has been evaluated and a parametric analysis has been carried out varying the user peak consumption. For each scenario, two in-house-developed software have been applied to find the optimal size of CHP systems and their optimal load allocation. The paper is structured as follows: in Section 2 the energy load profiles for three typical days (respectively representative of wintertime, middle season and summertime) of a medium size hospital facility (set as Reference Case) are shown and discussed. Furthermore, in Section 3 the methodology of the study is presented: in particular, the two developed and applied software operation is described, and the scenarios and the assumptions of the parametric analysis are presented. Then, in Section 4 the results obtained from the simulations are presented and discussed, in order to particularly highlight the achieved general aspects and results. Finally, in Section 5 the concluding remarks of the work are summarized.

2. Energy loads

In order to define the energy loads profiles for the medium size hospital facility, object of this paper, three typical days have been considered, respectively for wintertime, middle season and summertime. For these three representative days and based on literature

Table 1
Peak loads for the Reference Case.

Electrical Peak Load	1700 kW_e
Thermal Peak Load	5525 kW_{th}
Cooling Peak Load	5950 kW_c

review [25–27], the hospital energy consumptions – in terms of electrical, thermal and cooling needs hourly profiles for unit volume (W/m^3) – have been determined and presented in Fig. 1.

As it regards the wintertime typical day, Fig. 1 shows that both electrical and thermal needs are always greater than zero: the electrical load profile is low and quite constant during the night (between 11 p.m. and 6 a.m.), while the peak load is registered around 9 a.m. and 11 a.m. (equal to 4 W/m^3). Similarly, the thermal needs are lower during the night and present three peak loads respectively at 8 a.m. 11 a.m. and 5 p.m. (for all the cases equal to around 13 W/m^3). Furthermore, for evident reasons, no cooling needs for air-conditioning is considered during wintertime.

As it concerns middle season, instead, Fig. 1 shows that the thermal load profile is sensibly reduced, due to the only request of hot water (no space heating need is considered for this season) with peaks load approximately equal to 3 W/m^3. On the other hand, the electricity need is kept constant all over the year and no cooling need is required during middle season as well as for wintertime.

Finally, as it can be observed in Fig. 1 for the summertime typical day, the thermal and the electricity needs are the same already observed for middle season, while the cooling need profile of the hospital facility is very significant, representing one of the more relevant user consumptions (comparable to the wintertime thermal need). The peak of cooling need (equal to about 14 W/m^3) is registered between 2 p.m. and 3 p.m., while the minimum is reached during the night (no cooling energy is required between 1 a.m. and 3 a.m.). For completeness, it should be pointed out that the electrical need is intended as the one for lightning, hospital machinery operation, etc. (i.e. not considering electrical consumption for cooling).

As previously mentioned, this study is intended to be oriented to medium size hospital facilities: for this reason, a volume equal to 425'000 m^3 (corresponding to a medium size hospital with 600 beds [28]) has been chosen as starting point for the analysis, allowing to define the Reference Case. On the basis of the volume, the Reference Case peak loads of electrical, thermal and cooling needs have been determined and listed in Table 1.

3. Methodology

The analysis has been carried out according to the following steps: (i) definition of the production systems set-up, namely the choice and sizing of optimal systems (CHP units, heat pumps and boilers for heat production, as well as refrigeration chillers) to guarantee the user needs, (ii) optimal scheduling over a whole year of the selected systems in order to minimize the operational costs. This methodology has been firstly applied for the medium size hospital facility introduced in the previous section (the so-called Reference Case). Then, a parametric analysis has been carried out varying the peak power needs of the user, with the purpose of evaluating the effect of the peak load variation on the optimal size and scheduling of the energy systems.

As it concerns the first step, the optimal set-up and size of the energy production systems has been performed by means of an in-house developed software, named TRIGEN 3.0. The application of this software allowed in particular to set the typology (internal combustion engine or gas turbine) and the proper size of the cogeneration unit(s), as well as the cooling machines typology (compression and/or absorption chillers) to be installed at the hospital facility. Once defined the set-up of the production station, the optimization of the systems operation during a whole year has been carried out by means of a second in-house developed software named EGO (Energy Grid Optimizer), based on genetic algorithm. Finally, an economic analysis has been carried out, in order to compare the proposed innovative scenarios (CHP units, heat pumps and absorption chillers coupled with traditional systems for energy production) with the most adopted production set-up within hospital facilities sector (natural gas boilers for heat production and compression chillers for cooling production, electricity entirely purchased from the grid). The description of the applied two codes, the analyzed scenarios and the main considered assumptions are presented in the following paragraphs.

3.1. Optimal sizing of the cogeneration system: description of the software TRIGEN 3.0

The software TRIGEN 3.0 has been developed in Visual Basic for Application and it is aimed to carry out feasibility studies on co/tri-generation systems. On the basis of various inputs, the software is able to evaluate the installation of CHP unit ex novo or compared to other existing systems, also accounting for the current European cogeneration regulation (European Parliament directive 2004/8/CE and following modifications). The evaluation is made for a whole year of operation and can be extended up to 20 years of plant operation. The main required input parameters are:

- the user needs (thermal - divided between high and low temperature need, cooling and electric needs) for a whole year, hourly based;
- the typology of user (domestic, hospital, school, etc.);
- the electricity tariff scenario (electric energy cost, eventually differentiated based on the considered day and/or hour of the day);
- the fuel cost;

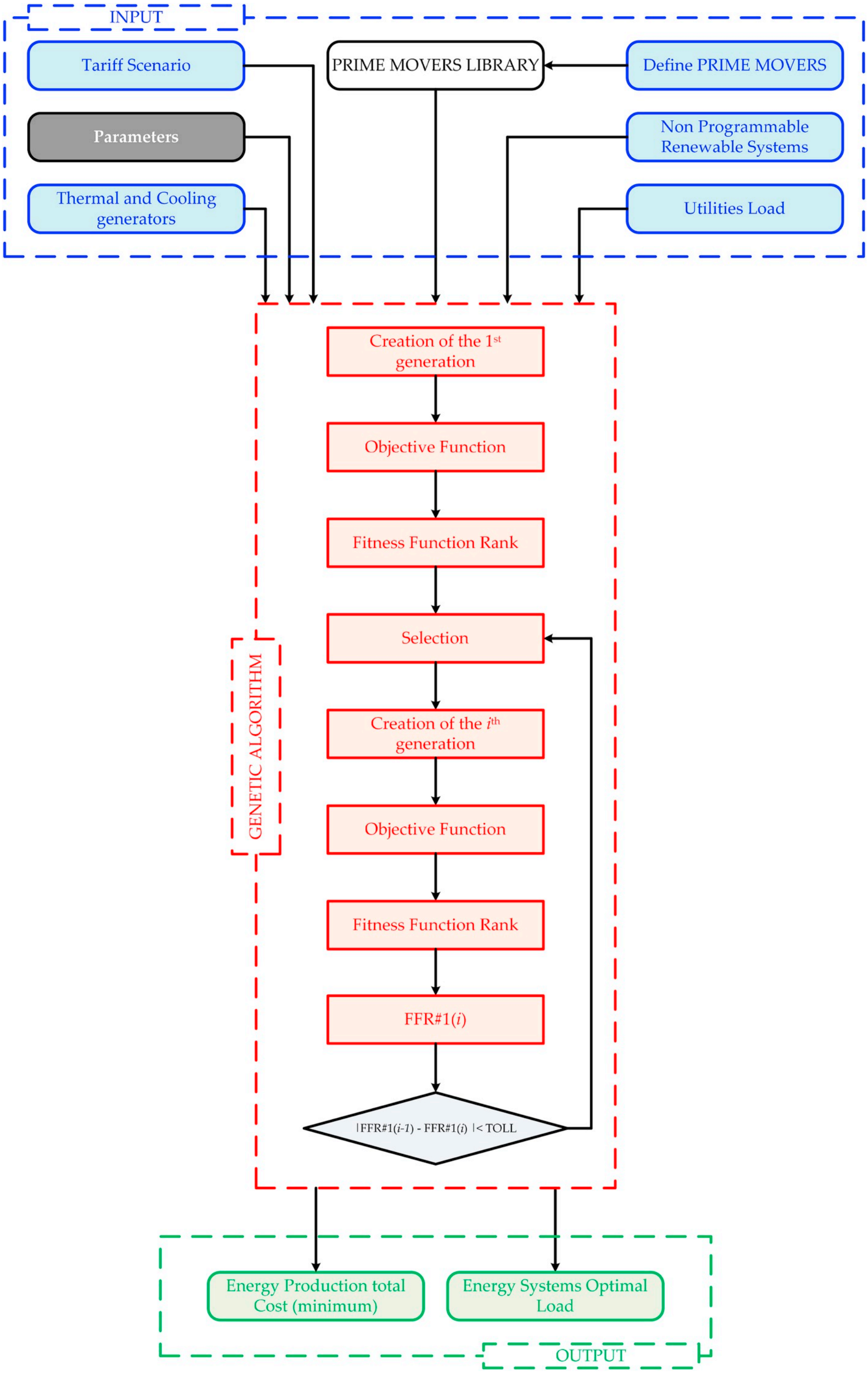

Fig. 2. Main flow chart of the EGO calculation code.

- the location of the production station. Based on this information an internal library will provide for the climate information (i.e. ambient temperature values for the entire year);
- the control strategy (i.e. following thermal or electrical need);
- the pollutant emissions factors.

An internal database with the main micro Gas Turbines (m-GT) and Internal Combustion Engines (ICE) available on the market is present, in order to select the best CHP unit for the considered application. Furthermore, before running the code, the cogeneration regulation which has to be applied is required: in other words, the software contains right inside the last regulations (starting from 2002) promoted by European Union and implemented by national governments. Obviously in the major cases the last regulation is the one to be considered, but this choice guarantees the possibility of evaluations also in plants operating when other regulations were in force.

The main output of the Trigen 3.0 calculation code are thermodynamic (energy production and consumption during the year), economic (operational and maintenance cost of the analyzed systems) and the results related to the CHP regulations. The results are provided not only numerically, but also graphically (for example, displaying the hourly energy profile for yearly typical weeks – one per month or the primary energy saving value on the thermal efficiency – electrical efficiency).

3.2. Load distribution and interaction within the energy grid: description of the software EGO based on genetic algorithm procedure

The software EGO (Energy Grids Optimizer), developed by the researchers of energy system group (University of Bologna), is able to define the load distribution of a number of energy systems operating within a complex energy grid, with the aim to minimize the total cost of the energy production. In more detail, the developed calculation code is able to simulate an energy grid, considering (i) an arbitrary number of prime movers (PM) eventually in CHP application, (ii) renewable source generators (solar thermal panels, wind turbines and photovoltaic panels), (iii) energy storage devices (for both electrical and thermal energy storage), (iv) heat generators (such as auxiliary boilers and heat pumps), (v) cooling machines (compression and absorption chillers). The previous production systems are used to cover the electrical, thermal and cooling energy loads required by a certain number of users. Furthermore, the electricity grid is connected with the national electrical grid and the natural gas distribution network connection is included. The calculation core of the software, presented in Fig. 2, consists in a genetic algorithm based on the minimization of an objective function (also called fitness function, FF), which expresses the total cost related to the energy production. The fitness function is expressed as follows:

$$FF = C_\lambda + C_M + C_E + C_F \tag{1}$$

where C_λ represents the total cost of fuel, C_M the total maintenance cost of the energy systems, C_E the total cost of the electricity purchased from the national grid and C_F are the so-called fictitious costs. Specifically, the four quantities which compose equation (1) are calculated as:

$$C_\lambda = \left[\sum_{i=1}^{n_{PM}} f_{\lambda,i}^{PM}(L_{PM,i}) + \sum_{i=1}^{n_{AB}} f_{\lambda,i}^{AB}(L_{AB,i}) \right] \cdot \lambda_{fuel} \tag{2}$$

$$C_M = \sum_{i=1}^{n_{PM}+n_{RGe}} P_{e,i} \cdot \mu_{e,i} + \sum_{i=1}^{n_{RGt}+n_{AB}+n_{HP}} P_{th,i} \cdot \mu_{th,i} + \sum_{i=1}^{n_{CC}+n_{AC}} P_{c,i} \cdot \mu_{c,i} \tag{3}$$

$$C_E = P_{e,P} \cdot \xi_{e,P} \tag{4}$$

$$C_F = \sum_{i=1}^{n_{PM}} \frac{Q_{dis,i}}{\eta_{AB,av}} \cdot \lambda_{fuel} \cdot p_T - P_{e,S} \cdot \xi_{e,S} \; or \; C_F = P_{e,S} \cdot \xi_{e,S} \cdot p_E \tag{5}$$

in case of thermal priority or electrical priority respectively.

In equations (2)–(5), λ_{fuel} is the specific cost (€/kW) of the fuel introduced in prime movers and auxiliary boilers (the most of the times natural gas), while $L_{PM,i}$ and $L_{AB,i}$ are the loads of the i-th prime mover and of the i-th auxiliary boiler respectively. The functions $f_{\lambda,i}^{PM}$ and $f_{\lambda,i}^{AB}$ express the power introduced with fuel in the i-th prime mover or auxiliary boiler as function of the systems load ($L_{PM,i}$ or $L_{AB,i}$). Regarding the maintenance costs, it is accounted as function of the produced power – electrical ($P_{e,i}$), thermal ($P_{th,i}$) or cooling ($P_{c,i}$) – of each system applying the corresponding maintenance cost specific values (μ_i expressed in €/kW). The total cost of the electricity purchased from the network, instead, can be estimated as function of the specific cost of purchased electricity $\xi_{e,P}$ (€/kW) and of the total electric power from the distribution network to the users $P_{e,P}$. Finally, a deeper explanation about the fictitious costs C_F has to be made: this quantity represents a term which forces the regulation strategy of the whole smart grid. The developed software, indeed, is able to consider and apply a *thermal priority* or an *electrical priority* for the energy systems' scheduling optimization. When the thermal priority regulation is applied, whit the purpose to minimize the environmental impact of the prime movers, a fictitious cost has been introduced to take into account the dissipation of thermal energy available from the prime movers and not supplied to the users. This cost is accounted as a multiple (p_T) of the fuel cost to produce the same amount of dispersed heat in a conventional boiler. An average conversion efficiency value, $\eta_{AB,av}$, is considered. With this regulation strategy, if more electricity is generated compared to users' needs and storage availability, the surplus can be sold to the network. The sale of electricity to the network is accounted as a reduction of the costs of electricity production considering a specific value $\xi_{e,S}$ (€/kW). On the other hand, the electrical priority regulation discourages the introduction of electricity into the grid, considering – contrarily to the previous case – this option as a cost. Similarly, in this option, a multiplication factor (p_E) has been applied, while the dissipation of heat from the prime movers to the environment is not considered as a cost. This strategy can be adopted, as an example, in case of a smart grid not connected to the network or if the national grid is not suitable to accommodate energy.

Table 2
Assumptions made for the production systems considered in the analysis.

Auxiliary Boilers Efficiency	85%
EER Compression Chillers	3.00
EER Absorption Chillers	0.67
COP Heat Pump	4.00
Mode of operation CHP Unit	Following thermal need
Installation site	Bologna (44°29′37″ N, 11°20′19″ E)
Winter season	183 days/year
Summer season	92 days/year
Middle season	90 days/year
Specific Cost for Electricity purchase	0.180 €/kWh
Specific Price for electricity sale	0.080 €/kWh
Specific Cost of Fuel	0.824 €/Sm^3
Maintenance cost CHP unit	0.020 €/kWh$_e$
Maintenance cost auxiliary boilers	0.005 €/kWh$_{th}$
Maintenance cost Heat Pump	0.010 €/kWh$_{th}$
Maintenance cost compression chiller	0.006 €/kWh$_c$
Maintenance cost absorption chiller	0.002 €/kWh$_c$

With the aim to minimize the fitness function, the developed genetic algorithm creates and/or evolves a population of candidate solutions, in which the chromosomes of each individual are represented by the loads (L_i) of the systems installed in the smart grid. After the creation of the first generation, the FF is estimated for each individual and a FF rank (FFR) is created. The individuals with lower values of FF (i.e. lower values of cost of energy production) are recognized as high rank solutions, while the ones with higher values of FF are classified as low rank solutions. The last 25 % of the lower rank solutions is automatically eliminated from the generation. The remaining 75 % of possible solutions is instead used to generate the individuals of the next generation. Among the different recognized possibilities for the generation of two new individuals starting from two parent individuals, the developed algorithm adopts the crossover method (also known as recombination method) without mutation. The selection of the parent individuals is realized with a roulette method: this method guarantees that individuals with higher rank have higher probability (from a statistical point of view) of generating a new individual. Except for the first generation, the highest rank solution FFR#1(i) of each generation is compared with the corresponding of the previous generation, FFR#1(i-1). The procedure ends when the absolute value of the difference between these two quantities becomes lower than a given tolerance value. Specifically, the required input functions are:

- electrical, thermal and cooling power required by the users; moreover, it is also possible to define the gas demand (for direct use) for the users;
- definition of the number, typology, and main characteristics of prime movers (electrical and thermal design power output, efficiency, off-design behavior, etc.), renewable source generators (peak power, performance, etc.), heating and cooling systems (size, performance, off-design behavior, etc.), electrical and thermal energy storage devices (maximum storable energy, temperatures and state of charge constraints, efficiency, etc.);
- the tariff scenario (purchased and sold electrical energy value, cost of the fuel, etc.);
- a series of parameters characteristic of the genetic algorithm.

The software's main output consists in the operation scheduling of each involved energy system, in order to minimize the total cost of energy for the users. A detailed description of the algorithm and deeper discussion on the software are presented in Ref. [29,30].

3.3. Parametric analysis and assumptions

In order to define the optimal production set-up and scheduling for small/medium size hospital facilities and to evaluate the effect of the energy demand variation on these aspects, a parametric analysis has been carried out starting from the Reference Case presented in Section 2. In more detail, the following scenarios have been evaluated and compared:

- *Case 1: the peak loads – for electrical, thermal and cooling needs – are equal to the half of the Reference Case corresponding ones;*
- *Case 2: in this case the peak loads are assumed equal to the 75 % with respect to the Reference Case values;*
- *Case 3: the peak loads – for electrical, thermal and cooling needs – are the double of the Reference Case corresponding ones.*

These scenarios have been firstly analyzed by means of the above described Trigen 3.0 software, allowing to select and design the machines for each case, based on the energy demands. The possibility to install internal combustion engines and/or gas turbines as cogeneration units has been investigated, as well as the opportunity to produce cooling energy by means of absorption and/or compression chillers. Furthermore, heat pumps and auxiliary boilers will provide for the remaining amount of thermal need after the CHP heat exploitation. The size of all these systems is also a result of the first step analysis. Therefore, on the basis of the obtained results, the optimal load allocation for the above mentioned different scenarios is the result of the simulations performed by means of the genetic algorithm EGO here adopted (second step analysis), where the input parameters are the production systems as well as the user energy demand (heat, cooling and electrical energy needs). In particular, three typical days have been considered for the analysis

Table 3
Production systems design results.

	Case 1	Case 2	Reference Case		Case 3	
CHP Unit						
Typology	ICE	ICE	ICE #1	ICE #2	ICE #1	ICE #2
Manufacturer	AB Energy	AB Energy	AB Energy	AB Energy	Deutz Power Systems	Deutz Power Systems
Model	ECOMAX 9	ECOMAX13 BIO	ECOMAX 9	ECOMAX 9	TCG 2020 V16	TCG 2020 V16
Rated Electrical Power	842 kW_e	1244 kW_e	842 kW_e	842 kW_e	1600 kW_e	1600 kW_e
Net Electrical Efficiency	0.411	0.416	0.411	0.411	0.425	0.425
Available Heat	925 kW_{th}	1238 kW_{th}	925 kW_{th}	925 kW_{th}	1584 kW_{th}	1584 kW_{th}
Investment Cost	782 €/kW_e	708 €/kW_e	782 €/kW_e	782 €/kW_e	661 €/kW_e	661 €/kW_e
Heat Pumps						
Total rated thermal power	1500 kW_{th}	2500 kW_{th}	3000 kW_{th}		6000 kW_{th}	
COP	4.00	4.00	4.00		4.00	
Investment Cost	200 €/kW_{th}	200 €/kW_{th}	200 €/kW_{th}		200 €/kW_{th}	
Auxiliary Boilers						
Total rated thermal power	3000 kW_{th}	4500 kW_{th}	6000 kW_{th}		12000 kW_{th}	
Efficiency	85%	85%	85%		85%	
Investment Cost	50 €/kW_{th}	50 €/kW_{th}	50 €/kW_{th}		50 €/kW_{th}	
Compression Chillers						
Total rated cooling power	3000 kW_c	5000 kW_c	6000 kW_c		12000 kW_c	
EER	3.00	3.00	3.00		3.00	
Investment Cost	350 €/kW_c	350 €/kW_c	350 €/kW_c		350 €/kW_c	
Absorption Chillers						
Total rated cooling power	300 kW_c	350 kW_c	550 kW_c		750 kW_c	
EER	0.67	0.67	0.67		0.67	
Investment Cost	350 €/kW_c	350 €/kW_c	350 €/kW_c		350 €/kW_c	

(see Fig. 1 for the energy needs), representative respectively of wintertime, spring/fall seasons and summertime. The made assumptions are presented in Table 2. In particular, the purpose is to avoid/minimize the heat dissipation, thus the following of thermal needs is considered for the CHP unit operation. Furthermore, since the Trigen 3.0 software requires the definition of the climate data for the considered installation site (mainly external ambient temperature profile during a year), the city of Bologna (North of Italy) has been chosen and considered. In order to further compare the results, finally, the differential Net Present Value (DeltaNPV) and the Return On Investment (ROI) have been calculated for the various analyzed configurations, based on the obtained optimal scheduling of the production systems and on the economical parameters presented in Table 2. It is worth mentioning that the DeltaNPV concept represents – for each case – the difference between the NPV of the considered case and the NPV which would be obtained whit traditional production systems set-up (i.e. exclusively natural gas boilers for heat production, compression chillers for cooling energy production and electricity entirely purchased from the grid). Additionally, investment and operational costs have been considered, as well as the tariff scenario for the electricity and the natural gas markets. As it concerns the fuel cost, in order to give more generality to the analysis, the incentives defined by national (Italian) framework on cogeneration have not been contemplated.

4. Results and discussions

The results of the application of Trigen 3.0 software are shown in Table 3. Obviously, with the augmentation in user's energy needs (the ascending order is Case 1, Case 2, Reference Case and Case 3), the size of the energy systems results increased. As it regards the combined heat and power units, the installation of Internal Combustion Engines (ICEs) is always preferable to the installation of micro-Gas Turbines (mGTs) due to conversion efficiency and economic reasons. Furthermore, an important result of the ICEs design optimization can be observed for the Reference Case as well as for Case 3: for these above mentioned two scenarios the installation of two CHP units with equal rated power (equal to the half of the electrical peak power required by the user) is preferable to the installation of only one ICE with a rated power equal to the peak load. This result allows higher flexibility in the CHP units operation during the year. The heat pumps thermal rated power, instead, is proportional to the peak power increase and it varies from 1500 kW_{th} for Case 1 to 6000 kW_{th} for Case 3. In addition, it should be highlighted that – as it can be observed from Table 3 – for each analyzed case the compression chiller is sized in order to cover the demand peak, as well as the auxiliary boilers installed power relating to the thermal peak. For safety reasons, indeed, since for the considered typology of user the fulfillment of energy needs is mandatory, installed auxiliary boilers and compression chillers usually have to completely guarantee by themselves the peak of thermal and cooling needs, respectively. Thus, the addition of different production systems entails a variation in their energy production during a year, but not in the size to be installed. Furthermore, the absorption chillers optimal size results very low with respect to the peak power need, being able to cover about the $7 \div 10$ % of the cooling peak load. Finally, in Table 3 the specific investment costs related to each of the considered systems are presented.

Therefore, the optimal scheduling for the production systems has been obtained, by means of the software EGO, for each analyzed scenario. As a first result, in Fig. 3 the CHP units optimal loads profiles are presented, for typical days in wintertime, middle season and summertime. As previously highlighted, the aim of the scheduling optimization is the minimization of the energy production costs, with the constraints of minimizing (avoiding) the dissipation of ICE available heat and the electricity into the grid. Based on pure observation from Fig. 3a, during wintertime the high thermal energy needs allow – for all the scenarios – a great exploitation of the

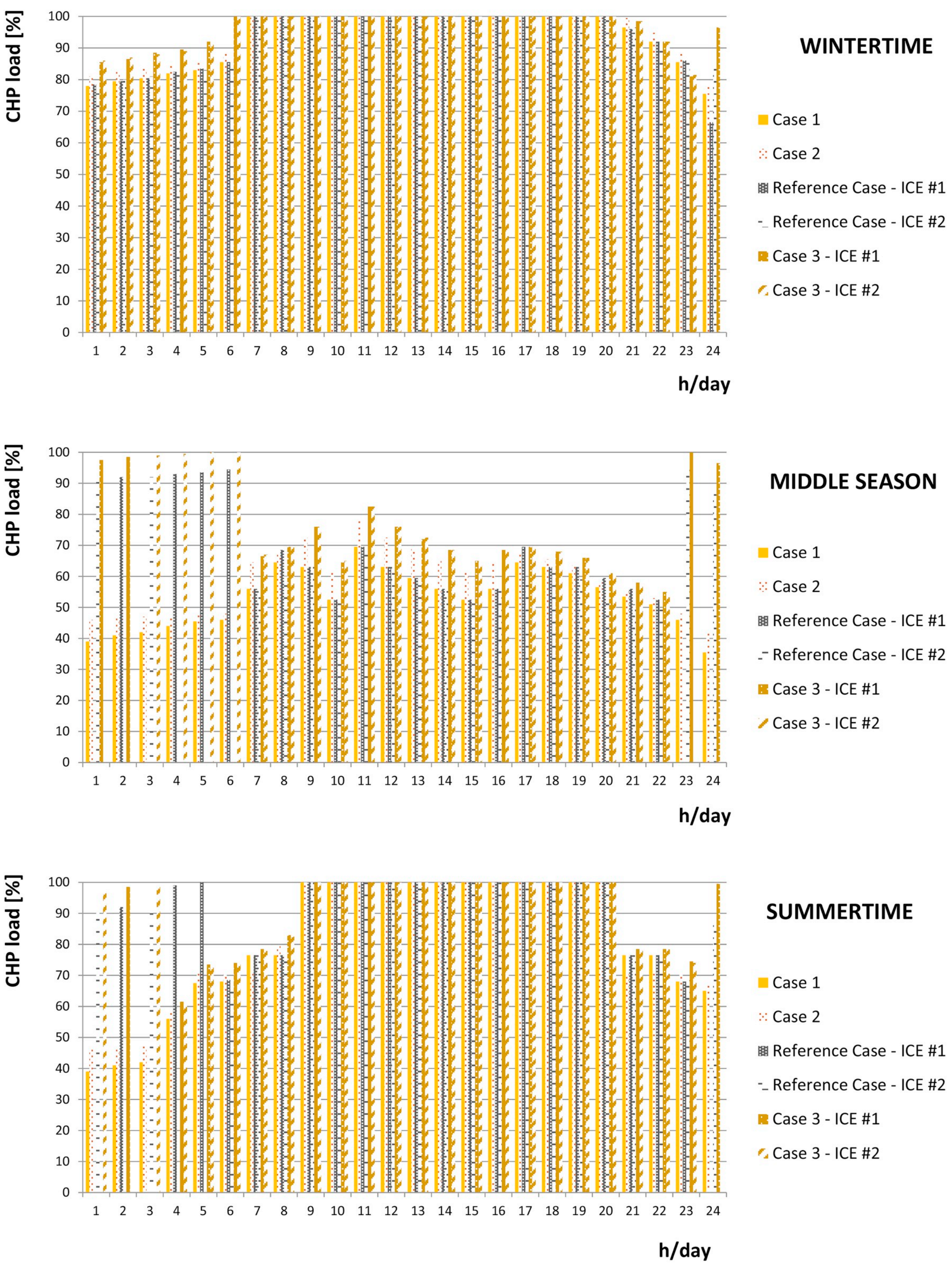

Fig. 3. CHP units load profiles during a typical day in: a) wintertime, b) middle season and c) summertime, for the analyzed cases.

cogeneration systems, thanks to the installation of heat pumps fed by the electricity surplus. In fact, all the CHP units operate at full load from 7 a.m. to 8 p.m., while during the rest of the day their load is always higher than the 75 % of their rated power. During the middle season (see Fig. 3b), instead, the contemporary absence of space heating and cooling needs, importantly reduces the ICEs

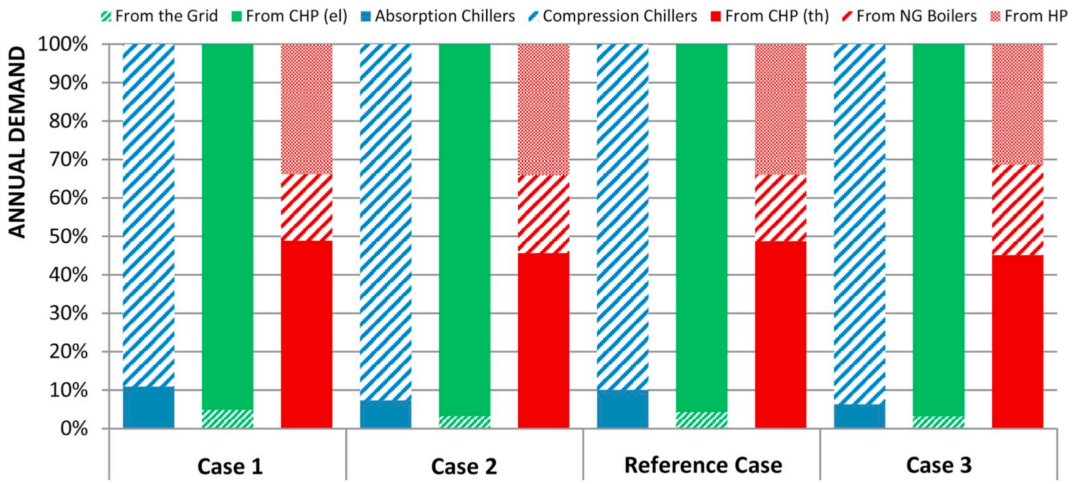

Fig. 4. Yearly user energy needs fulfillment mix, for the considered cases: cooling needs (in blue), electrical needs (in green) and thermal needs (in red). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

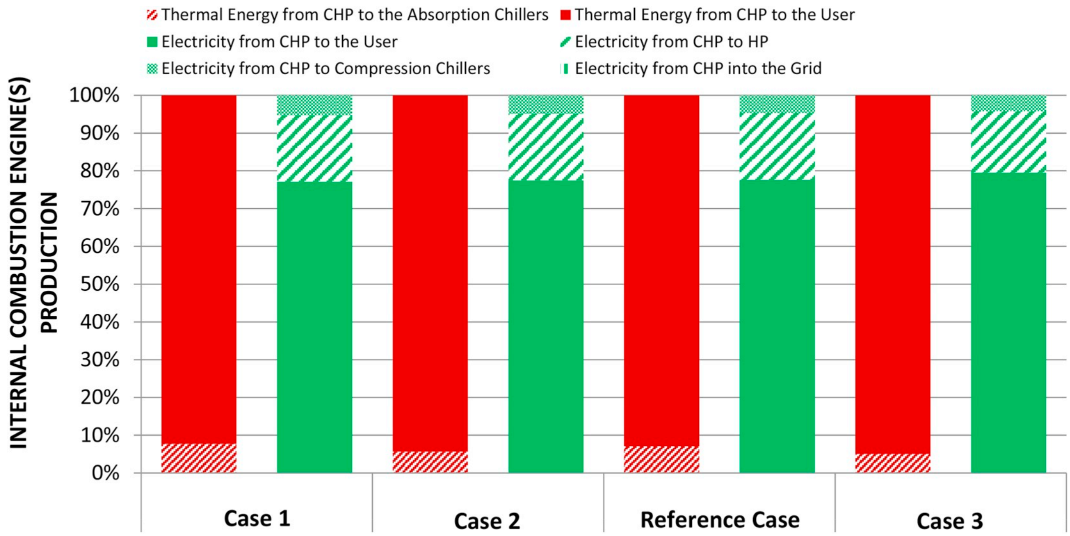

Fig. 5. Yearly CHP electrical (in green) and thermal (in red) production divided between its different employments, for the considered cases. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

operation. However, relating to the Reference Case and to Case 3, the decision to install two CHP units instead of one enables to use these units also during middle season when the thermal loads are very low. Finally, from Fig. 3c it can be observed that, during summertime, the cooling loads – fulfilled by both compression and absorption chillers – allows a good exploitation of ICEs: for all cases CHPs operate at full load from 9 a.m. to 8 p.m., while a reduction is observed during the night. In particular, from 1 a.m. to 5 a.m. some ICEs are not in operation due to the low cooling energy request.

Therefore, the energy results are presented in Fig. 4 and in Fig. 5. Specifically, Fig. 4 shows the user's yearly energy demand (electrical, thermal and cooling), along with the fulfillment mix, for the different analyzed scenarios. As it can be seen, the percentages of electrical needs covered by the CHP unit(s) and by the national electrical grid change with the variation of the peak load. This is mainly due to the choice of commercial machines, thus with a ratio between user's peak demand and CHP rated power not quite the same for each case. However, the most significant result consists in the fact that the CHP production is able to cover between the 95 % (Case 1: 4'574'571 kWh/year from the CHP on an overall electrical request of 4'809'941 kWh/year) and almost the 97 % (Case 3: 18'612'855 kWh/year from the CHP on an overall electrical request of 19'235'500 kWh/year) of the users electrical needs. As a consequence, the amount of electrical energy to be annually purchased from the nation grid is very low. Regarding the thermal needs fulfillment, the CHP units behavior follows the corresponding electrical one: for Case 1 and for the Reference Case, indeed, a higher amount ICEs produced heat (slightly lower than the 50 %) is exploited for the thermal user needs fulfillment – with respect to Case 2 and Case 3 (respectively around 45 % and 44 % of thermal demand covered by CHP production). Another important contribution to the

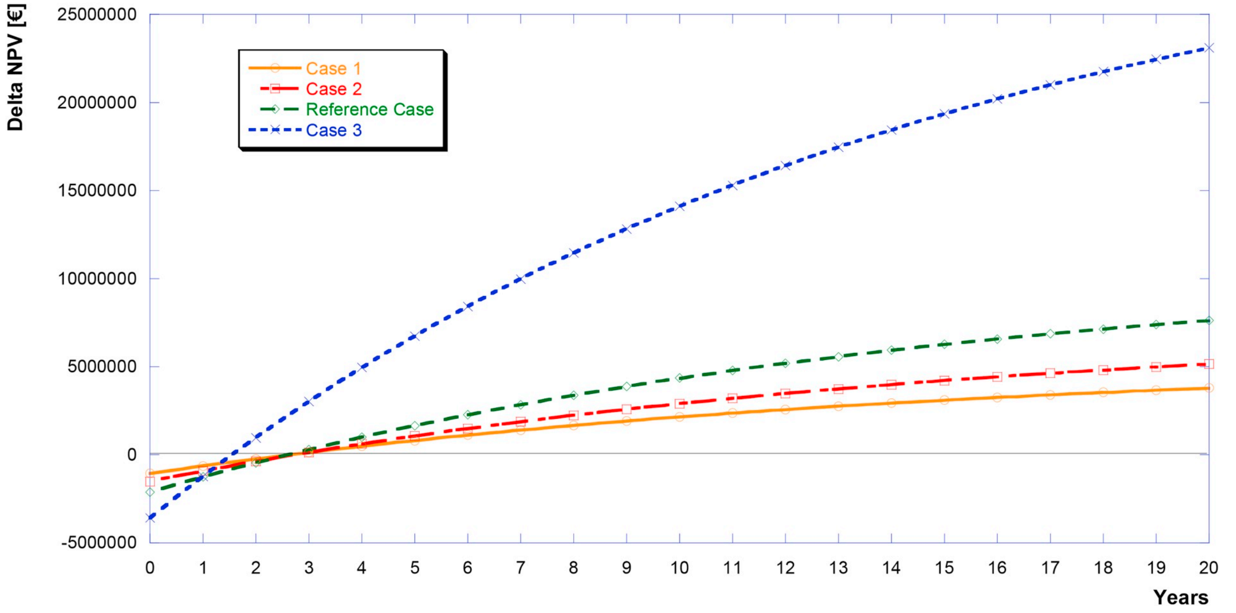

Fig. 6. Trend of the net present value difference – between the considered scenarios and their corresponding base cases (no cogeneration units nor heat pumps and absorption chillers; gas boilers and compression chillers for energy production, electrical grid connection) – over a 20 years horizon, as function of the considered case.

thermal energy requested by the user is given by the heat pumps, which are always able to cover more than the 30 % of the thermal demand, with a maximum percentage equal to the 34 % with reference to Case 2 (6'327031 kWh/year from HP on an overall thermal request equal to 18'546'469 kWh/year). The remaining amount of the user thermal need is satisfied by natural gas boilers production, representing the energy systems which give the minor contribution (ranging from 17 % – Reference Case to 23.5 % – Case 3). In other words, the simultaneous installation of cogeneration systems and heat pumps allows to reduce the natural gas boilers exploitation up to the 83 %. The economic aspects will be better treated in the following of this section, but it results evident that – in an international perspective of promoting energy efficiency increase and cogeneration, even in presence of incentives – this outcome is particularly interesting. Finally, relating to the cooling energy, for all the scenarios the results show that the compression chillers produce the higher amount of requested cooling energy, while the absorption chillers production ranges between the 6 % (Case 3: 782742 kWh/year) and almost the 11 % (Case 1: 337839 kWh/year) of the cooling needs.

On the other hand, the CHP units production of electrical and thermal energy is presented in Fig. 5, along with the different employments of this produced energy. The electricity produced by the ICE can be (i) used for the fulfillment of user needs itself, (ii) fed to the heat pump, (iii) fed to the compression chillers or (iv) introduced into the national electric grid. As it can be seen in Fig. 5, an amount slightly lower than the 80 % of the ICE electrical production is used for the hospital facility needs fulfillment. Secondly, the ICE electricity is used to move the heat pumps and the compression chillers, while the introduction into the network is negligible. This last contribution, indeed, cannot be appreciated in Fig. 5, being less than the 0.01 % of the total production for all the cases, and it confirms the quality of the adopted optimization strategy. In fact, both electricity purchase and introduction into the network are minimized by the application of the software EGO with a simultaneous complete avoid of dissipated heat from the ICEs. Regarding the ICE thermal production, it can be utilized for the user needs fulfillment and/or for the absorption chillers feeding. As it can be noted from Fig. 5, the major part of the heat available from the cogenerator(s) is employed for the user's needs fulfillment, while only a small amount is used for cooling energy production. This evidence is clearly due to the high thermal needs and considering that the ICEs are sized accounting the electrical peak loads.

Finally, the results of the economic analysis are briefly shown in Fig. 6, in terms of trend of the delta net present value – between the analyzed cases and the corresponding base case (no cogeneration considered, gas boilers and compression chillers for energy production, electrical grid connection) – considering a 20 years horizon and a discount rate equal to the 7 %. Based on pure observation, Fig. 6 shows that the return of investment is around 3 years for Case 1, Case 2 and Reference Case, while it is less than 2 years for the Case 3. Obviously, with the augmentation in the user peak loads (i.e. moving from Case 1 to Case 3), the installation cost increases. However, this economic analysis has been intended in order to verify and demonstrate the convenience of the introduction of cogeneration coupled with heat pumps in hospital facility sector. The short times for the return of investment seem to indicate this way as viable and interesting solution for these kinds of applications. Moreover, further benefits can be achieved if an incentives scenario for CHP is considered.

5. Conclusions

The achievement of optimal energy and economic results by means of combined heat and power plants is a complex problem that requires multi-objective optimization approach, because the dependence is not only due to plant configuration but also to regulation, management strategies, tariff scenarios etc. In this context, a co/tri-generation plant for a hospital facility has been here studied, including heat pump and absorption chillers installation. More specifically, a parametric analysis has been carried out starting from a medium size hospital facility set as Reference Case. For each of the analyzed cases, the optimal plant configuration (sizing of all cogeneration units) has been outlined by means of a numerical code (Trigen 3.0) in-house developed. Afterwards, in order to optimize the load distribution in a smart grid characterized by electrical, thermal, cooling and fuel energy fluxes, a further numerical investigation has been outlined by means of the in-house developed EGO code (Energy Grids Optimizer), based on genetic algorithm procedure.

The economic analysis shows a ROI ranging from 1.5 to 3 years and a Net Present Value, over a 20 years horizon, varying from 3.8 M€ to about 23 M€ depending on facility peak loads. This economic analysis has been intended in order to verify and demonstrate the convenience of the introduction of cogeneration coupled with heat pumps in hospital facility sector. The short times for the return of investment seem to indicate this way as viable and interesting solution for these kinds of applications. Moreover, further benefits can be achieved if an incentives scenario for CHP is considered. Finally, the achieved results allow to generalize the sizing of the CHP power plant by considering the following coefficients:

- CHP Design Electrical Power/Hospital Electrical Peak: 0.94–1.00
- CHP Design Thermal Power/CHP Design Electrical Power: 0.90–1.00
- HP Design Thermal Power/Hospital Thermal Peak: 0.54–0.60
- AC Design Cooling Power/Hospital Cooling Peak: 0.06–0.10
- CC Design Cooling Power/Hospital Cooling Peak: 1.0
- AB Design Thermal Power/Hospital Thermal Peak: 1.1

As evident, it is worth mentioning that the previous values refer to medium size hospital facilities with a ratio between thermal and electrical peak loads equal to about 3.3 and a ratio between cooling and electrical peak loads equal to 3.5.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.csite.2019.100525.

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