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Combined Heat and Power Generation Systems Design for Residential Houses

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Abstract

Nowadays cogeneration is recognized as one of the most effective techniques to meet the increasingly stringent requirements regarding energy efficiency increase and energy saving in buildings. In this context, the aim of this study is the definition of reference parameters for the optimal energy systems design in residential applications. To this purpose, a generation scenario with cogeneration units, heat pumps, auxiliary boilers and chillers (both compression and absorption machines) has been set for the fulfillment of residential users' needs (in terms of electrical, thermal and cooling loads). For a given number of involved households, commercial cogeneration units have been selected, sized on the basis of the electrical peak need, and the generation scenario has been optimized by an in-house developed software, obtaining the optimal energy systems design and operation. Then, a parametric analysis has been carried out varying the number of considered households in order to define the optimal range of the energy systems size. In particular, specific values in terms of installed power for household and installed power for unitary peak load have been determined. For completeness, an economic analysis has been finally carried out for the evaluation of the return on investment and of the differential net present value – with respect to a standard generation scenario (only natural gas boilers for thermal needs fulfillment and electricity purchase from the grid for electrical and cooling needs) – considering a time horizon of ten years.

Keywords: Cogeneration; Parametric Analysis; Design and Scheduling Optimization; Design Parameters; Residential Application.

1. Introduction

The increasing interest in energy savings is affecting, besides commercial and industrial sectors, even the residential one, essentially due to the strong correlation with the global environment and resources [1]. On this regard, combined heat and power systems (CHP) are largely employed in residential sector since they allow to reach over 80 % of energy efficiency conversion against the 30-35 % of the conventional power generation [2]. Therefore, cogeneration results to be an effective generation method, able to achieve significant benefits in terms of efficiency, environmental impact and economic costs [3]. Different cogeneration technologies can be adopted for residential applications, in particular internal combustion engines and micro gas turbines. Other possibilities – even if less economically viable at present – are fuel cells, Stirling engines and micro Organic Rankine Cycles [4]. The introduction of these systems poses new issues, mainly related to the proper design and scheduling (*i.e.* the load allocation between the various energy systems), especially in combination with distributed generation [5-6]. For this purpose, several optimization techniques can be adopted, such as heuristic or exact methods [7-9].

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The aim of the paper is the definition of general guidelines to identify the different energy generation systems optimal size for residential applications. In order to reach this goal – starting from the non-dimensional hourly profiles of the electrical, thermal and cooling needs for a single residential unit differentiated between three typical days (representative of wintertime, middle season and summertime) – a parametric analysis has been carried out, varying the number of considered household units from 100 to 1000. The generation systems scenario, set for the whole analysis, consists in internal combustion engines (operating as cogeneration units), natural gas auxiliary boilers, heat pumps, compression and absorption chillers. During the analysis, an in-house developed software, based on genetic algorithms [10], has been employed in order to optimize the design and operation of the considered production systems. Finally, for the sake of completeness, an economic analysis has been performed.

2. Methodology

2.1. Energy Loads

The household energy demand for a typical residential unit mainly consists of electrical energy (for lighting, computer side, cold and/or hot appliance, etc.), thermal energy (for hot water and – in winter season – space heating) and cooling energy (for air conditioning in summer season). As starting point of this study, electrical [11], thermal [12] and cooling [13] dimensionless load curves, available from literature, have been considered. As it regards the electrical loads, three different profiles have been accounted, because electrical energy demand is quite different depending on the considered season. This is mainly due to the electrical consumption of cold appliance. Relating to the thermal needs, instead, two non-dimensional profiles have been considered, respectively for space heating and hot water needs. Thus, both space heating and hot water needs are considered for winter season, while only hot water need occurs during summertime and middle season. Finally, the cooling energy demand occurs only during summertime. Based on the previous considerations, three typical days have been defined, respectively representative of wintertime, middle season and summertime. Furthermore, in Tab. 1 the electrical, thermal and cooling specific peak loads are listed [12, 14]. In addition, a surface equal to 80 m^2 has been considered for each residential unit, being representative of a typical apartment. Based on these assumptions, the hourly load curves for a residential unit and for each typical day have been evaluated. In more detail, the resulting electrical, thermal and cooling dimensional load profiles for winter, summer and spring-fall season are presented in Fig. 1.a, Fig. 1.b and Fig. 1.c respectively [12, 14].

Table 1. Assumed specific peak loads for thermal, electrical and cooling needs [12, 14].

Peak loads	Units	Value
Space heating	[kWh/m^2 y]	220
Hot water	[kWh/m^2 y]	30
Electricity	[kWh/m^2 y]	30
Cooling	[kWh/m^2 y]	44

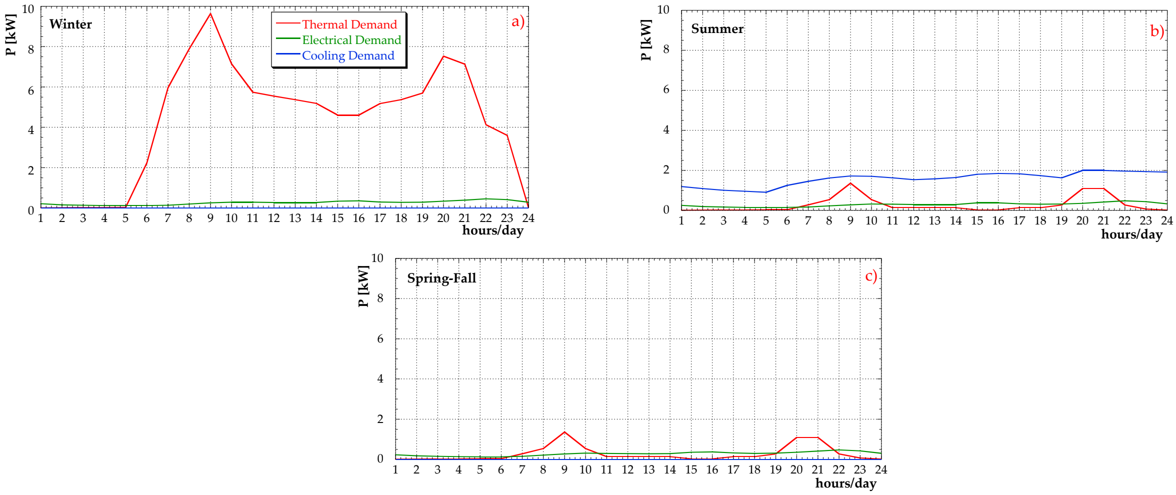

Fig. 1. Hourly load curves for a residential unit during typical winter (a), summer (b) and spring-fall (c) days [12, 14].

Finally, with reference to Italians' regulations, the following seasons' partition during the year has been hypothesized:

- winter: 183 days;

- summer: 92 days;
- middle season: 90 days.

2.2. Software EGO and Parametric Analysis

In order to proper design and schedule the energy systems depending on the user demand, an in-house developed software, named EGO (Energy Grid Optimizer) has been applied [10]. This software, developed for the optimal scheduling definition within complex energy networks, is based on genetic algorithm and – starting from the thermal, electrical and cooling users' needs – it is able to define the energy systems operational profile during a year. Differently from other approach, such as Mixed Integer Programming, the adoption of genetic algorithm allows to find one of the possible optimal solution for problems with a high complexity by retaining the influences of nonlinear phenomena and with an acceptable computation time. The core of the calculation code consists in the minimization of a fitness function which accounts the total costs of energy production. In particular, the EGO application allows to define the optimal load allocation with the purpose of (*i*) maximizing the CHP operation (*ii*) minimizing or completely avoiding the thermal dissipations to the chimney and (*iii*) minimizing the electricity exchange with the electric grid. In order to account these aspects, additional fictitious costs can be considered for electrical energy exchange with the electrical grid and/or for the heat dissipations. In more detail, the software input section requires:

- the number, typology and main characteristics of the generation systems – such as prime movers, renewable generators, auxiliary boilers, energy storage devices, compressor chiller, etc. – composing the network;
- the tariff scenario (the electricity purchase cost and sale price, the fuel cost, etc.);
- other parameters that characterize the genetic algorithm.

A detailed description of the algorithm along with the mathematical model and the software validation can be found in [10].

Since the aim of this study is the definition of the optimal generation systems size for a given number of residential users, the software EGO has been applied – starting from the load profiles for a single residential unit presented in the previous section – within a parametric analysis on varying the number of considered residential unit from 100 to 1000 with a step of 100 users.

2.3. Hypothesis and Assumptions

The possibility to exploit different energy systems for the users' needs fulfilment has been evaluated. In particular, cogeneration systems have been considered for heat and electricity production, as well as heat pumps and natural gas auxiliary boilers – for thermal needs – and the electrical grid connection – for electrical needs. The cooling need is supposed to be satisfied by means of absorption and/or compression chillers. In this study, as first approach, the adoption of thermal energy storage for heat recovery has not been taken into account. The thermal storage application could be investigated in future works.

As it concerns cogeneration systems, internal combustion engines (ICEs) have been considered based on an internal database of the software containing a large amount of commercial CHP systems. As it will be shown in the results section, the size of these systems has been selected – for given number of considered residential units – on the basis of the electrical peak need. Furthermore, the off-design curves for the ICEs required by the software have been modelled as described in [15]. On the other hand, the values of the performance parameters for the heat pump, auxiliary boilers and cooling machines – assumed for the whole analysis – are listed in Table 2 [16]. These design parameters have been kept constant during the whole parametric analysis, for the off-design behavior and with the variation of the size. The determination of the size for each production system, instead, is the object of the carried-out study.

Table 2. Performance design parameters constant for the whole analysis [16].

Parameter	Value
Heat Pump COP	4.00
Auxiliary Boilers Efficiency	0.85
Compression Chiller EER	3.50
Absorption Chiller EER	0.67

2.4. Economic Analysis

In order to give a complete analysis and to compare the defined optimal generation systems' set-up with the traditional configuration in residential sector, an economic analysis has been carried out. To this purpose, for each considered number of residential units, a Reference Case has been defined, assuming that energy demand is satisfied only by the natural gas boilers and by the purchase from the electrical grid. In detail, the economic evaluation is based on the differential Net Present Value (with respect to the Reference Case) considering a time horizon of 10 years. The specific investment costs of each generation system assumed for the calculation, along with the maintenance costs, are listed in Table 3. As it regards the operational costs, a constant value equal to 0.180 €/kWh$_e$ has been assumed for the purchased electrical energy, regardless the time frame, and a price equal to 0.824 €/Sm^3 is considered for natural gas. Finally, the return on investment has been evaluated for each case.

Table 3. Maintenance and Investment Costs assumed for the economic analysis.

	Maintenance Costs	Investment Costs
CHP Unit	0.020 €/kWh$_e$	500 €/kW$_e$
Auxiliary Boilers	0.005 €/kWh$_{th}$	50 €/kW$_{th}$
Heat Pump	0.010 €/kWh$_{th}$	200 €/kW$_{th}$
Compression Chiller	0.006 €/kWh$_c$	350 €/kW$_c$
Absorption Chiller	0.002 €/kWh$_c$	350 €/kW$_c$

3. Results and Discussion

In Table 4 the design parameters of the selected ICEs are listed for all the analyzed cases. In order to minimize (or avoid) the electricity introduction into the network, each of these CHP units has been chosen from the EGO commercial internal database considering the users electrical peak needs. As it can be seen from the table, Natural Gas (NG) fuel is common for all the ICEs while the design electrical and thermal efficiency vary depending on the model and not only with the size. This aspect obviously affects the operation results of the ICEs. As it regards the other energy systems, as will be shown in the follows, the optimal size is a result of the simulations.

Table 4. CHP systems design parameters.

# Households	100	200	300	400	500	600*	700	800	900	1000
Manufacturer	EMD	Energifera	Ecogen	EMD	Stone Power	Ecogen	MDE	MDE	EMD	Caterpillar
Model	EMD 45	TEMA 100	EG140	EMD 200	2230	EG140	ME 3042 L	ME 3042 Z	EMD 400	G3508 LE
Fuel	NG	NG	NG	NG	NG	NG	NG	NG	NG	NG
Design Electrical Power [kW]	45	95	140	190	236	140	337	386	400	480
Design Thermal Power [kW]	63	170	207	290	372	207	525	541	500	631
Design Electrical Efficiency [-]	0.325	0.321	0.351	0.319	0.354	0.351	0.350	0.364	0.414	0.369
Design Thermal Efficiency [-]	0.455	0.574	0.519	0.487	0.558	0.519	0.545	0.510	0.518	0.485

*Two ICEs of this model have been considered for this case.

Considering the ICEs presented in Table 4, the yearly energy results of the scheduling optimization are shown along with the generation mix in Fig. 2, Fig. 3 and Fig. 4 – respectively in terms of users' electrical, thermal and cooling needs – as function of households' number. In detail, more than the 65 % of the electrical users' needs is covered by the CHP units in all the considered cases (see Fig. 2), with a maximum equal to 70 % for the case of 900 households. Obviously, the remaining amount of electricity needs is provided by the national grid. As it regards the thermal needs, instead, the contribution of ICEs ranges from 12.7 % (900 households) to 17.9 % (200 households), while the one of heat pumps varies from 10.7 % (900 households) to 13.3 % (800 households). However, the higher percentage of thermal needs is fulfilled by the auxiliary boilers – from 69.5 % (200 households) to 76.6 % (900 households). Evidently, this result is a consequence of the choice to size the ICEs considering the electrical peak load, which is considerably lower than the thermal peak load. Finally, the cooling needs are almost entirely satisfied by the compression chillers, ranging from around 88 % (200 households) to around 92 %. (1000 households). The absorption chillers – since they can be fed exclusively by the ICE heat production – cover only the remaining small percentage of cooling needs.

On the basis of the carried-out simulations, the optimal energy systems' size is defined and presented in Fig. 5 for each case. As expected, the optimal size of the auxiliary boilers and of the compression chillers increases linearly with the number of considered households. On the other hand, some energy systems – such as heat pumps and absorption chillers – present a different behavior, with a size variation trend not proportional with the residential units' number. This evidence is a result of the application of the genetic algorithm.

Relating to the economic analysis, the results in terms of differential net present value (for a time horizon equal to 10 years) and of return on investment are listed in Table 5 for each case. As it can be observed, the two investigated parameters cannot be univocally correlated to the increase of the involved number of households. In particular, the worst case is represented by 100 households (return on investment equal to 10 y and minimum differential net present value), while the best case is represented by 900 households (return on investment equal to 4 y and maximum differential net present value). This is due to several factors resulting from the optimization – in terms of fuel consumption, electricity purchase and heat recovery – and related to the equivalent hours of operation of the various considered energy systems. From the simulations, indeed, the best case results the one that better exploit both the ICE and absorption chiller (maximum equivalent hours of operation for both these production systems). As it regards the other energy systems, instead, their employment is almost the same in the considered cases.

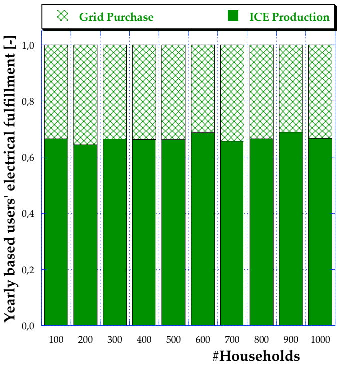

Fig. 2. Non-dimensional users' electrical needs, along with the generation mix considering a year of operation.

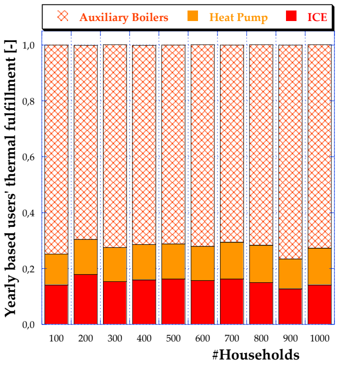

Fig. 3. Non-dimensional users' thermal needs, along with the generation mix considering a year of operation.

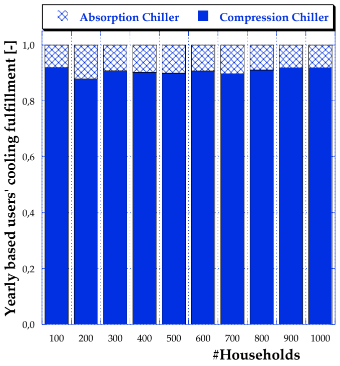

Fig. 4. Non-dimensional users' cooling needs, along with the generation mix considering a year of operation.

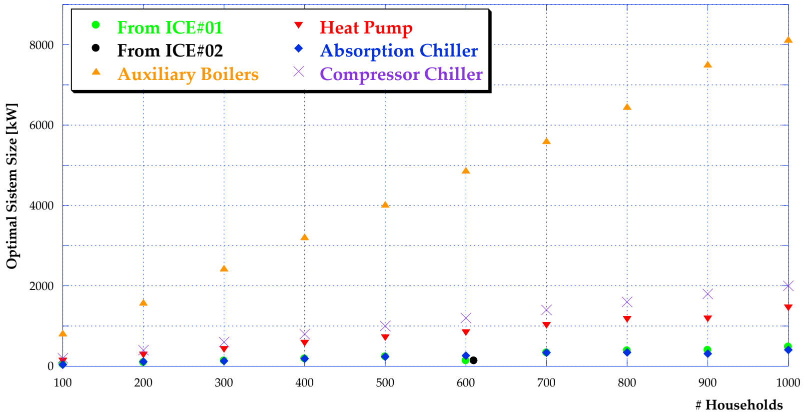

Fig. 5. Optimal energy systems' size.

On the basis of the previous considerations, the final result of the presented analysis is the optimal range of the energy systems' specific size – evaluated with respect to the number of households and to the peak load. As a consequence, within the proposed energy systems set-up scenario, the following specific values can be considered as reference parameters for the energy systems optimal design in residential applications:

- ICE: 0.4-0.5 [kW$_e$/household] or 0.5-1.0 [kW$_e$/kW$_{peak}$]
- Heat pump: 1.3-1.5 [kW$_{th}$/household] or 0.1-0.2 [kW$_{th}$/kW$_{peak}$]
- Auxiliary boilers: 7.9-8.4 [kW$_{th}$/household] or 0.8-0.9 [kW$_{th}$/kW$_{peak}$]
- Compression chiller: 2.0 [kW$_c$/household] or 1.0 [kW$_c$/kW$_{peak}$]
- Absorption chiller: 0.3-0.6 [kW$_c$/household] or 0.2-0.3 [kW$_c$/kW$_{peak}$]

Table 5. Differential Net Present Value for a time horizon equal to 10 years and Return of Investment for each case.

# Households	100	200	300	400	500	600	700	800	900	1000
Differential Net Present Value [€]	1'407	179'901	223'705	134'713	520'243	471'053	703'402	733'026	869'025	787'781
Return on Investment [y]	10	5	5	7	4	5	4	5	4	5

4. Concluding Remarks

The aim of the paper is the definition of general guidelines to identify the optimal energy systems design in residential sector, by considering a generation scenario, for the residential users' needs fulfilment, consisting in internal combustion engine as cogeneration units, natural gas auxiliary boilers, heat pump, compression and absorption chillers. To this purpose, a parametric analysis has been carried-out, varying the number of considered residential units from 100 to 1000 with a step of 100 users. For the analysis, commercial internal combustion engines have been chosen, sized on the electrical peek need of a given number of considered residential units. Then, the analysis has been conducted by implementing the software EGO (Energy Grid Optimizer), based on genetic algorithms, that allows to evaluate the optimal yearly operational set-up by minimizing both the energy production costs, the exchange of electric energy with the national electric grid and the thermal energy dissipations. For completeness, an economic analysis has been performed.

As a result of the simulations, for each households' number considered case, the yearly energy users' fulfillment – in terms of electrical, thermal and cooling needs – is shown, along with the generation mix resulting from the scheduling optimization. Furthermore, for each case, the optimal energy systems' size is presented. As it regards the auxiliary boilers and the compression chillers sizes, as expected, they linearly increase with the considered household numbers. Conversely, the other energy systems optimal sizes present a non-proportional trend with the variation of the considered residential units, mainly due to the genetic algorithm application. Relating to the economic analysis, the differential net present value (for a time horizon of 10 years) and the return on investment have been determined for each case. The results show that the two parameters cannot be univocally correlated to the residential units' number increase, due to both the optimization factors – concerning the fuel consumption, the electricity purchase and heat recovery – and the equivalent hours of operation of each considered energy production system.

Finally, the last result of the analysis is the optimal range of the energy systems' specific size, evaluated with respect to the number of households and to the peak load. The resulting specific values can be considered as reference parameters for the energy systems optimal design in residential applications.

Nomenclature

c	cooling
CHP	Combined Heat and Power
COP	Coefficient of Performance
e	electrical
EER	Energy Efficiency Ratio
EGO	Energy Grid Optimizer
ICE	Internal Combustion Engine
NG	Natural Gas
th	thermal

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