Optimization of integrated CCHP and solar plants following a multi-objective approach. An application to the household sector.

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Abstract- Integrated Energy Systems for buildings constitute one of the most strategic solution for achieving the current objectives in the energy sector. Integration broadens the possibilities for the diffusion of district heating and cooling systems, for a wider Renewable Energy Sources exploitation, for the waste heat recovery and for the energy storage. Moreover, integrated systems can include cogeneration, certainly leading to primary energy needs and to CO2 emissions reduction but low carbon technologies imply relevant investments and an optimal solution for this trade-off behaviour has to be defined.

With this aim, a combined cooling heating and power system, based on an internal combustion engine and on an absorption heat pump, integrated to a solar collectors plant through a thermal energy storage, has been studied and applied to a group of apartments requiring heating, domestic hot water, cooling and electrical energy. A tailored model has been developed, able to optimize the system considering its peculiarities in a more easy and immediate way compared to the models available in literature, generally designed to study large-scale systems. Two different configurations have been studied: in the first the absorption heat pump is fed, during the warmer months, directly by the high temperature engine exhaust gases; in the second it's fed by the storage tank all the year. The procedure results are the optimal sizes of the devices (engine, solar plant, and, for the latter case, also the absorption heat pump) and the trade-off fronts, which show a greater convenience for the second case, where a stronger integration among the various devices is achieved and mean annual costs and CO2 emissions reduction of 25% and 35%, respectively, are obtained.

Keywords- CCHP; Thermal solar plants; Systems Integration; Multi-objective Optimization; Thermal Energy Storage.

1. Introduction

Due to the current EU policies, energy efficiency, reduction of Green House Gases (GHG) emissions and diffusion of Renewable Energy Sources (RES) for Europe Member States constitutes almost a mandatory goal. As known, in fact, the Climate-Energy Package [1], a set of binding legislation also known as "20-20-20", aims to ensure that the EU meets its ambitious climate and energy targets within 2020. The three key objectives for this year are: the 20% GHG emissions reduction from 1990 levels; the 20% raise of the share of EU energy consumption produced from RES; the 20% improvement in the EU's energy efficiency. In particular, the new EU Program "Horizon 2020" [2] pays a particular attention to the area of buildings, that account for 40% of EU final energy demand and also to that of technologies for District Heating (DH) and cooling. The program aims to reduce the energy consumption of space heating and cooling and of Domestic Hot Water (DHW) production by 30%-50% compared to today's level, and to contribute to a wider use of intelligent DH and cooling systems and integration of RES exploitation, waste heat recovery and energy storage [3]. In this context, development and deployment of efficient and environmentally sustainable Integrated Energy Systems (IES) for buildings constitute important elements for the the objectives set achieving. They combine on-site energy conversion and distributed generation technologies with thermally activated technologies to provide cooling, heating, humidity control, energy storage and/or other process functions using thermal energy usually wasted in the production of electricity/power [4-6]. For these purposes EU Member States have committed to energy efficiency as a key element in their energy policies and efficiency increase measures have started to give a relevant contribution on a significant scale. In particular, Combined Heat and Power (CHP), due to its important role to the primary energy consumption reduction [7], has evolved increasingly in recent years [8], extending to the Combined Cooling Heating and Power (CCHP, or trigeneration) applications, that could represent a strategic solution [9] for the household sector: e.g. in Italy, starting from the two last decades, the electric energy demand peak is gradually translating from the later afternoon of the coldest months, towards the late morning hours of the hottest ones for air conditioning needs [10]. Moreover, in small and medium scale applications, the Distributed Cogeneration (DC) offers new opportunities for the development of technologies integrating the exploitation of RES [11,12]. In fact, with particular reference to the solar energy [13], on one hand, it's widely available so it can give, with acceptable costs, a significant contribution to achieve the objectives expressed above; on the other hand, its intrinsic characteristics of non-continuity and non-programmability could be well mitigated by these kind of distributed systems [14,15].

Despite the DC characteristics, that allow for the reduction of the primary energy demand and of the GHG emissions, this practice is not widely spread and future outlooks do not forecast significant growth perspectives for the residential sector [16]. This is mainly due to two reasons.

The first is concerned with the lack of tools for the optimal system components and simultaneously of the optimal energy dispatch for small scale residential application. In fact, models available in literature are mainly based on thermodynamic approaches [17,18], which also integrate thermo-economics [19-21] and pinch analysis procedures [22,23], and also on mixed-integer linear/non-linear (MILP/MINLP) [24-27]. All of these are able to describe complex situations related to medium-large scale users clusters and lead to the sizing of complex power distribution networks consisting of many production sites and articulated distribution systems.

The second reason derives from the uncertainties of the end-user to valorise the externalities due to the avoided GHG emissions.

To face these issues, in this work a model, easily applicable to the residential sector, for the design and dispatch optimization of an integrated system proposed as a redevelopment work of a hypothesized Ante Operam (AO) traditional system, has been developed. The system is constituted of a CHP plant based on an Internal Combustion Engine (ICE)† extended to CCHP through an Absorption Heat Pump (AHP) and by a low-temperature Solar Collectors (SC) system integrated through a Thermal Energy Storage (TES). TES is able to act as a thermal inertia and can guarantee the deferral, even in the medium-long term, between the thermal energy produced and that used in different times. Two configurations for the connection of the AHP to the integrated system have been studied. In the first, the ICE exhaust gases thermal power feeds the AHP during the summer season and they are switched toward the TES in winter. In the second, the ICE exhaust gases thermal power is recovered at low temperature in the TES throughout the year and the AHP is fed by the low temperature heat coming from the TES. For the first case, a high AHP COP is possible; the second can lead to a better global efficiency due to a higher level of integration of the system components.

These energy systems need to reveal their actual convenience compared to an ordinary way of energy supply. In fact, many are the aspects that, at the same time, contribute to the costs, to the reduction of the primary energy consumption and to the reduction of GHG emissions, leading to situations of trade-off. Generally, in fact, the goal of optimal costs cannot be reconciled with the minimization of GHG emissions, realized through "carbon-free" technologies that require wide investments.

All the combination of the optimal sizes are given by the developed multi-objective optimization procedure in the form of a Pareto front, which constitutes a useful tool for the choice of solutions that prefer the economic or the environmental aspect.

2. The model

The model refers to a CCHP plant in which the key device is a TES, fed by a SC plant and by the thermal energy recovered from the ICE. If the thermal energy contributes are less than the user needs for heating and DHW, an auxiliary Boiler (B) provides the integration of thermal energy into the TES. The ICE, working in a CHP configuration, provides the electric energy required by the user and, eventually, by Compression Air Conditioning (CAC), the usual way of cooling energy supply, hypothesized for the AO, for the cooling energy integration. The ICE is connected to the grid for the eventual exchange of respectively surplus or lacks of the electricity. About the thermal energy produced by the ICE, the low temperature contribute flows into the TES through an Heat Exchanger (HE); a HE is provided also for the high temperature thermal energy, which feeds an Absorption Heat Pump (AHP) for the cooling needs.

In particular, two different situations of AHP connection have been studied. Case 1 (Fig. 1) is related to a plant layout in which the AHP is fed during the summer by the high temperature exhaust gases, that are conveyed in the storage

† Chosen for its suitable characteristics compared to the household energy requirements.

tank during the winter; in Case 2 (Fig. 2) the AHP is always connected to the tank for all the year.

For both Cases, the model solves the energy fluxes balances shown in the figures in terms of power, expressed by the equations (1), (2), (3), (4) related to the electrical, cooling, low and high temperature thermal powers, respectively.

Equations (1.a) and (1.b), valid for both Cases, are referred to the point A (Fig. 1 and Fig. 2), and take into account the integration and the transfer to the grid, respectively.

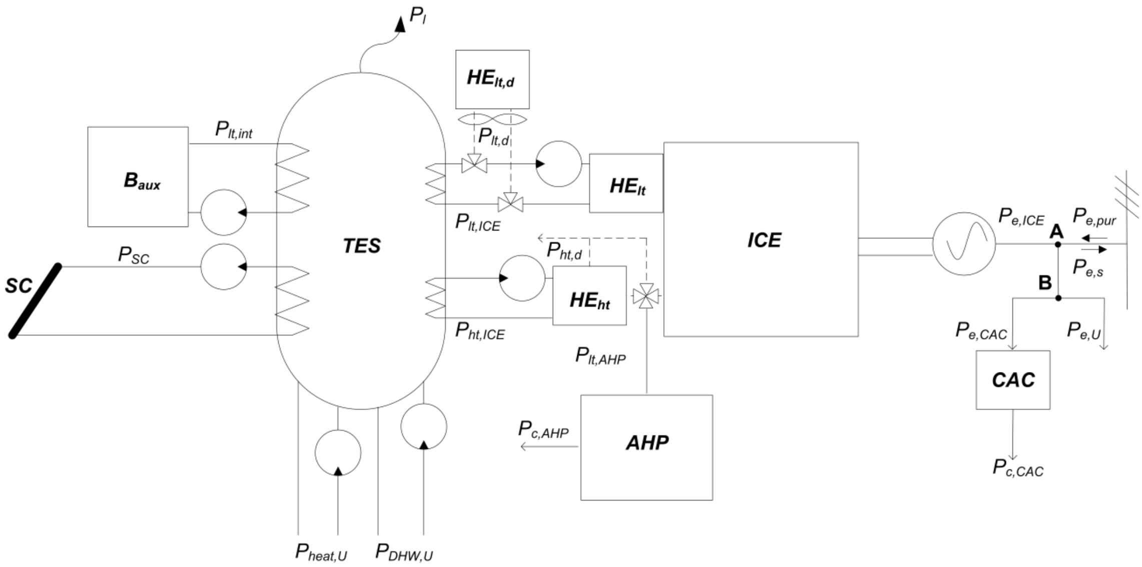

Fig. 1. Case 1 layout.

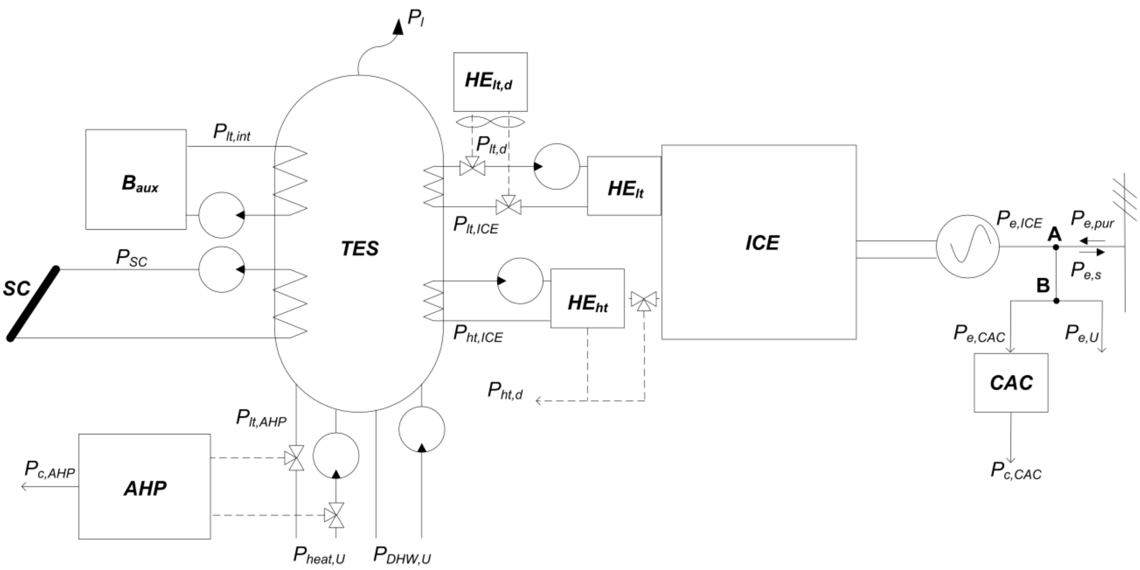

Fig. 2. Case 2 layout.

$$P_{e,ICE} + P_{e,pur}(t) - P_{e,U}(t) - P_{e,CAC}(t) = 0 \quad \text{if} \quad P_{e,ICE} - P_{e,U}(t) - P_{e,CAC}(t) < 0 \tag{1.a}$$

$$P_{e,ICE} - P_{e,s}(t) - P_{e,U}(t) - P_{e,CAC}(t) = 0 \quad \text{if} \quad P_{e,ICE} - P_{e,U}(t) - P_{e,CAC}(t) > 0 \tag{1.b}$$

$$P_{c,AHP} + P_{c,CAC}(t) - P_{c,U}(t) = 0 \quad \text{if} \quad P_{c,AHP} - P_{c,U}(t) < 0 \tag{2}$$

Equation (2), valid for both Cases, takes into account the cooling energy integration through CAC.

Regarding the low temperature thermal powers, in the balances of the equation (3.a) for Case 1 and of the equation (3.b) for Case 2, the contribution of the ICE is related to the heat recovery on the cooling and lubrication circuits; there are also the input of the solar plant and the output of the losses due to heat exchange from the TES , and, only for Case 2, the contribution of the AHP is present. For Case 2 there is also the contribution expressed in the balance on the equation (4), due to the connection of the AHP directly to the ICE.

$$\left(P_{lt,ICE} + P_{ht,ICE} + P_{lt,int}(t) + P_{SC}(t)\right) + \\ -\left(P_{heat,U}(t) + P_{DHW,U}(t) + P_{lt,d}(t) + P_l(t)\right) = m_{TES}\cdot c\cdot\frac{dT_{TES}(t)}{dt} \tag{3.a}$$

$$\left(P_{lt,ICE} + P_{ht,ICE}(t) + P_{lt,int}(t) + P_{SC}(t)\right) + \\ -\left(P_{heat,U}(t) + P_{DHW,U}(t) + P_{ht,d}(t) + P_{lt,AHP}(t) + P_{lt,d}(t) + P_l(t)\right) = \\ = m_{TES}\cdot c\cdot\frac{dT_{TES}(t)}{dt} \tag{3.b}$$

$$P_{ht,ICE} - P_{ht,d}(t) - P_{ht,AHP}(t) = 0 \quad \text{if} \quad P_{ht,ICE} - P_{ht,AHP}(t) > 0 \tag{4}$$

Starting from these energy balances, the model evaluates the Equivalent Annual Cost (EAC) and the CO_2 emissions (associated to the energy supply management and to the installation of the devices). They're the two elements required by the objective function, equation (5), to be minimized, in which they, both normalized with respect to the corresponding AO situations, constitute a cost-function (Fc, defined as the ratio of costs after and before the redevelopment) and a CO_2-function (FCO_2, defined as the ratio of the CO_2 mass emitted after and before the redevelopment), linearly combined through a weight factor (y) variable between 0 (emissions minimization) and 1 (costs minimization). The independent variables are $x_1=P_{e,ICE}$ and $x_2=A_{SC}$ for Case 1, while a further variable, $x3=P_{AHP}$, is added for Case 2.

$$F_{Ob}(x_i) = y\cdot F_C(x_i) + (1-y)\cdot F_{CO_2}(x_i) \tag{5}$$

Costs and CO_2 reductions with respect to the AO condition are obtained if F_c and F_{CO2} are lesser then one.

The TES size isn't a result of the optimization. In fact, it's exposed only to energetic constraints. In particular, to ensure the stability of the TES, in order to guarantee a long term operation, the following constraints are imposed:

- a periodic thermal regime, that in the end of the time period analysis is able to restore the fluid temperature into the same initial value;
- the limit of 10°C as the maximum temperature swing of the fluid, equation (6).

$$max\left(T_{TES}(t)\right) - min\left(T_{TES}(t)\right) \le \Delta T_{TES}. \tag{6}$$

For the TES a *lumped parameters* behaviour, with uniform temperature in the space, has been also assumed.

The optimization has been carried out through an algorithm for the minimum of constrained nonlinear multivariable function of the Matlab© package. The optimization results are in a trade-off front form in which each point is a possible configuration that could be assumed, preferring environmental (*y*=0) or economical aspect (*y*=1).

The model has been applied to conduct a feasibility study of a redevelopment work in the residential sector consisting in the integration of a new power plant, as replacement of the usual energy supply mode, e.g. from the distribution networks.

3. Assumptions

3.1. User needs

For the analysis, a complex of 360 apartments located in the north of Italy, each one with a surface equal to 50 m^2, arranged in eighteen two levels buildings has been hypothesized as user and connected with District Heating Network (DHN). For SC area, the upper bound of 5000 m^2 has been assumed, compatible to the limit of the surface available on the buildings roofs, equal to 9500 m^2. Energy needs profiles have been obtained from a software for the energy certification starting from data available in literature [28]. Electrical and thermal energy for the DHW production needs, present all months, have been evaluated as average values over the year; in these cases the reference weeks show the average trend of the load represented in Fig. 3 on a hourly basis. As regards the heating and cooling needs, present only in winter and summer months respectively, weeks with the maximum energy demands, e.g. February and July respectively, have been taken as the basis for the analysis, as shown, always on a hourly basis, in Fig. 3 (‡).

(‡) In the figure, the electric energy demand doesn't include the energy for CAC.

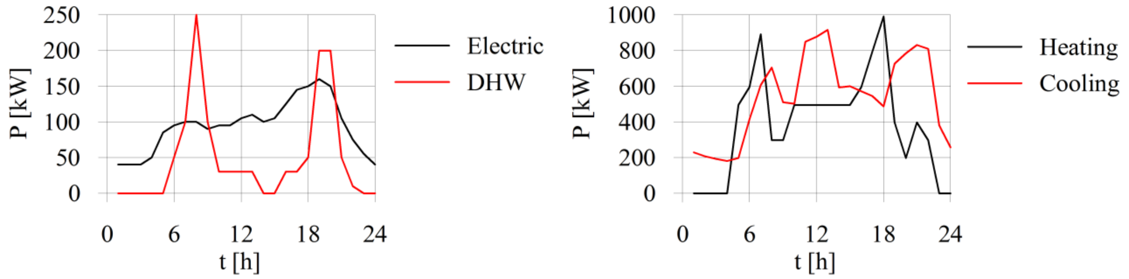

Fig. 3. User electric and DHW (on the left) and heating and cooling (on the right) hourly demand.

On an annual basis, the energy needs are: 77 kWh/m^2 for heating, 24 kWh/m^2 for DHW, 66 kWh/m^2 for cooling and 2200 kWh per apartment for electricity. These values are typical of the Italian context.

3.2. Main hypothesis for the plant devices

The ICE has been hypothesized operating at a fixed point, at nominal conditions. The recovered thermal power from the engine has been divided into equal parts for the high temperature exhaust gases and the low temperature refrigeration circuits; both electrical and thermal efficiency have been evaluated as function of the nominal engine power. The efficiency of SC, considered of the *evacuated tube* type, has been considered evaluated variable during the year. For TES a walls transmittance of 0.4 W/m^2.K has been assumed. The AHP, working with *lithium bromide* as fluid, is *double stage* type with COP equal to 1.4 for Case 1 and *single stage* type with COP equal to 0.65 for Case 2. CAC is an *inverter single split* and has COP equal to 3.2. Lastly, for the integration boilers, an efficiency equal to 0.9 has been assumed.

About the costs assumed for the described devices, Table 1 summarizes the unit costs, derived from the nowadays Italian market and considered variable with the size.

Costs of B and CAC have been not considered, due to their presence also in the AO plant configuration.

Table 1. Unit costs of plant devices

Component	**Unit cost**
ICE	- Investment: variable with the engine nominal power (1) - Maintenance, lubrication, ancillary costs: 30 €/MWh
SC	- Investment, comprehensive of balance of plant and maintenance: 300 €/m^2
AHP	- Investment: same as for the ICE (2)
TES	- Investment, comprehensive of balance of plant and maintenance: 150 €/m^3
DHN	- 1 €/m^3 (of air conditioned volume)

(1) e.g., for $P_{e,ICE}$ =150 kW, 1000 €/kW
(2) e.g., for $P_{c,AHP}$ =250 kW, 200 €/kW (single stage), 350 €/kW (double stage)

3.3. Tariffs and incentives for energy carriers

About the energy carriers prices and the possible incentives, they have been defined taking into account the Italian current market conditions for the residential sector. For electricity, the purchasing and selling tariffs have been assumed as 0.21 €/kWh and 0.09 €/kWh, respectively.

Natural gas has the cost of 0.455 €/m^3; a tax exemption is applied to a portion of the gas required by the engine if it respects the High Efficiency Cogeneration, HEC, conditions [29], evaluated through the calculation of the Primary Energy Saving, PES [30].

Other incentives are associated to the selling of the Energy Efficiency Credits, EEC [31] and to the tax deductions for the installation of the solar thermal system [32].

3.4. Other hypothesis

The technological life of the plant is 20 years and, in order to bring the analysis to an average year, all costs have been evaluated as EAC. Costs consider: investment, fuel, energy integration, O&M and the revenues from selling, tax deduction and credits.

About rates, 7% is assumed as the discount rate, while 3% and 2% consider the increases due to the inflation of the energy carriers prices and of other costs, respectively. The capital cost is assumed as 6%.

For the CO_2 mass evaluation, emission factors in a *standard* approach have been considered. These don't account the emissions from all stages of the life cycle of electricity and natural gas, neither the contribution of additional GHG. They are equal to 0.482 kg_{CO2}/kWh for electricity and 0.202 kg_{CO2}/kWh for natural gas [33].

The hourly solar radiation has been evaluated using the average monthly data available from UNI 10349 [34] and adapted as outlined in [35,36].

4. Results

4.1. Optimal devices sizes

Figures 4, 5, 6 are referred to the devices optimal sizes evaluated through the procedure for eleven values of the weight factor (varying from 0 to 1, with step 0.1).

About the ICE (Fig. 4), it's not present for *y* lesser than 0.4 for Case 1 and lesser than 0.5 for Case 2. In the latter Case lower $P_{e,ICE}$ values are also observed compared to that obtained for Case 1. Maximum values are observed in *y*=1, where the optimization is totally displaced towards the costs minimization.

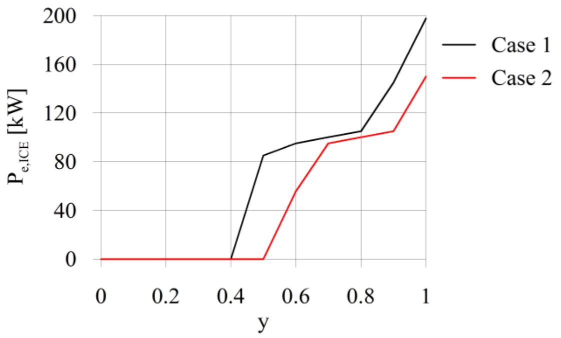

Fig. 4. ICE size as function of the parameter y.

The solar collectors area (Fig. 5) decreases as *y* increases, in a complementary way compared to $P_{e,ICE}$, reaching higher values in Case 2, where the solar plant has to compensate the lower heat power available from the engine.

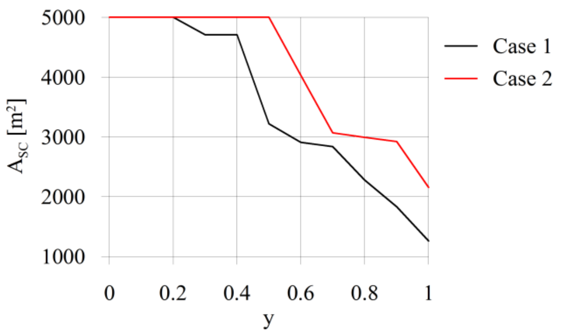

Fig. 5. SC area as a function of the parameter *y*.

The results obtained for the AHP (Fig. 6) reflect, for Case 1, the behavior observed for the ICE. In fact, in Case 1, the AHP is not object of the optimization, so, following the ICE, it's not present for *y* values lesser than 0.4. Instead, in Case 2, AHP, being it the third variable of the optimization, is present in all *y* range, contributing to reduce the integration through CAC, which requires the electric energy purchase from the grid, when $P_{e,ICE}$ =0. As $P_{e,ICE}$ increases P_{AHP} decreases because of the availability of the electric energy produced through CHP, cheaper than that from the network and then partly used to feed the CAC system.

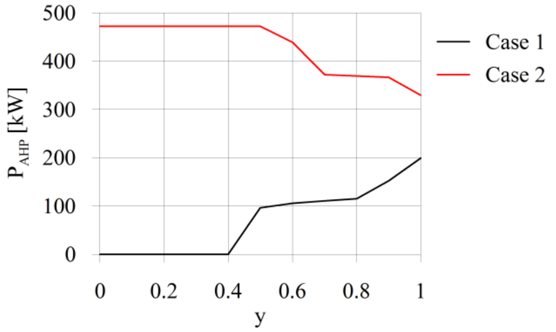

Fig. 6. AHP size as a function of the parameter *y*.

Due to this greater presence of AHP, and, also, to the more suitable solar power exploitation, for Case 2 a greater TES volume, shown in Fig. 7, is required with respect to Case 1.

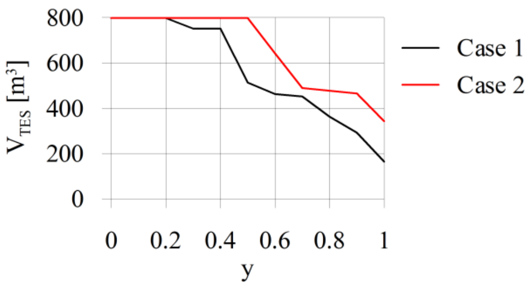

Fig. 7. TES volume as a function of the parameter *y*.

The optimization Pareto fronts are presented in Fig. 8. As already mentioned, costs and CO_2 reductions with respect to the AO condition are obtained if F_c and F_{CO2} are lesser then one, equation (5). This is verified for both if F_c and F_{CO2} except one point for F_{CO2} in Case 1. The front for Case 2 is totally below that for Case 1, implying, as expected, that the deeper level of integration among the devices conducts to a greater performance of the whole system.

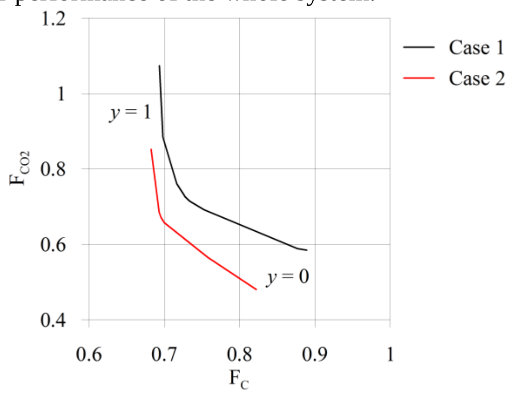

Fig. 8. Pareto fronts.

Table 2 summarizes the main optimization results for *y*=0 and *y*=1.

	Case 1					Case 2				
	F_C	F_{CO_2}	$P_{e,ICE}$ kW	A_{SC} m^2	P_{AHP} kW	F_C	F_{CO_2}	$P_{e,ICE}$ kW	A_{SC} m^2	P_{AHP} kW
$y=0$ (1)	0.890	0.595	0	5000	0	0.820	0.495	0	5000	460
$y=1$ (2)	0.695	1.080	200	1350	200	0.680	0.850	150	2100	330

(1) CO_2 emissions minimization
(2) Costs minimization

4.2. Energy balances

To evaluate the energy flows and the share-out among the various contributions, fig. 9, 10, 11, 12 show the energy annual balances for both Cases as a function of *y*. It's evident that they reflect the plant dimensioning results. In fact, for what concerns the electrical energy balance (Fig. 9), it shows that for *y* values higher than 0.4 for Case 1 and 0.5 for Case 2, the purchased energy immediately decreases, while the sold one progressively increases, especially in Case 1, due to higher values of ICE obtained for *y*=0.4.

For the same reason, in Case 1, being AHP size proportional to the ICE size, unlike that for Case 2, the electrical energy (for the user needs and for the CAC feeding) decreases as *y* increases. In fact, for Case 1, as ICE size increases, $E_{e,U}$ decreases, even if in a marginally way, due to the contribution of AHP that reduces the electrical energy for the CAC feeding. An opposite behaviour is observed for Case 2, where the contribution of the AHP (as will be observed discussing the following Fig. 10) decreases for *y*>0.5 and electric energy is required by the CAC.

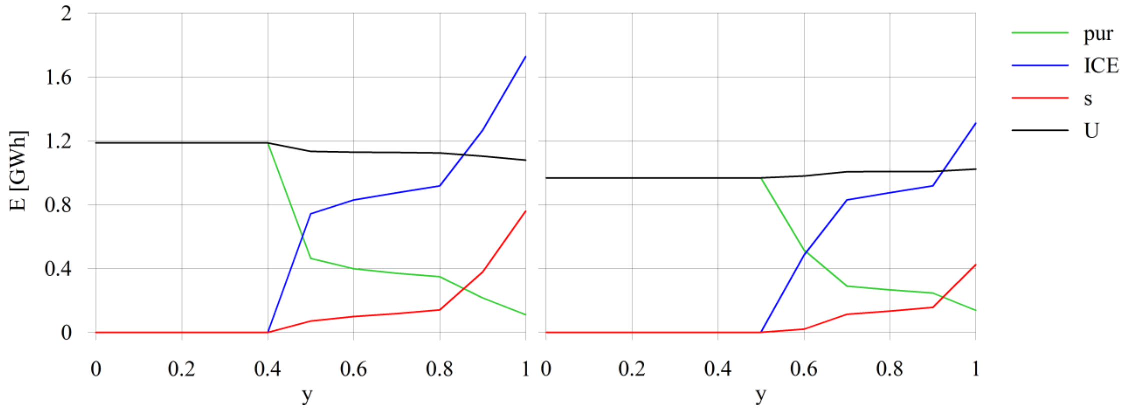

Fig. 9. Annual balance of the electrical energy for Case 1 (on the left) and Case 2 (on the right).

This aspect is further highlighted by the cooling balance (Fig. 10), where it's observed that for *y*=1 $E_{c,AHP}$ is about one third of the total. The opposite situation happens for Case 2, where the cooling energy from AHP has the greatest contribution.

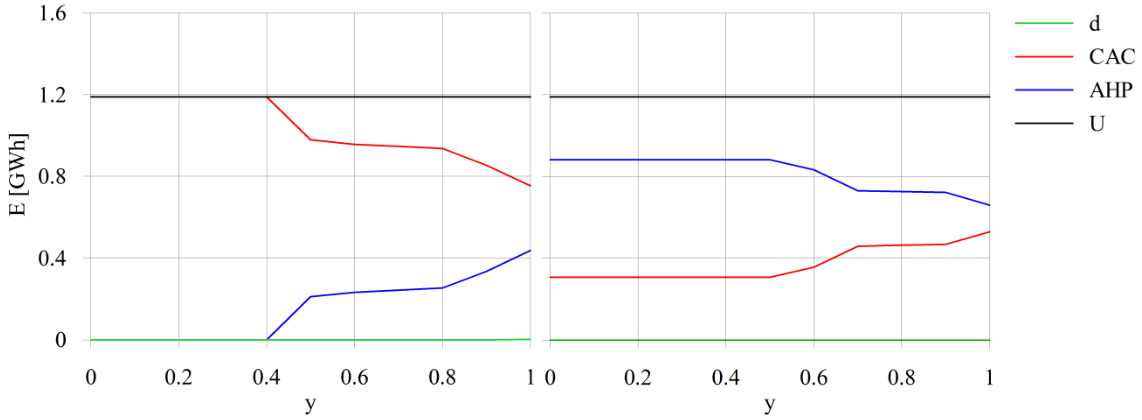

Fig. 10. Annual balance of the cooling energy for Case 1 (on the left) and Case 2 (on the right).

Fig. 11 shows the low temperature energy balance, more complex because of the greater number of contributions to the TES. Among these, for Case 2 it's also observed the presence of the high temperature energy from the ICE contribution, while in Case 1 it, not being switched toward the TES, is expressed separately in the high temperature energy balance of Fig. 12.

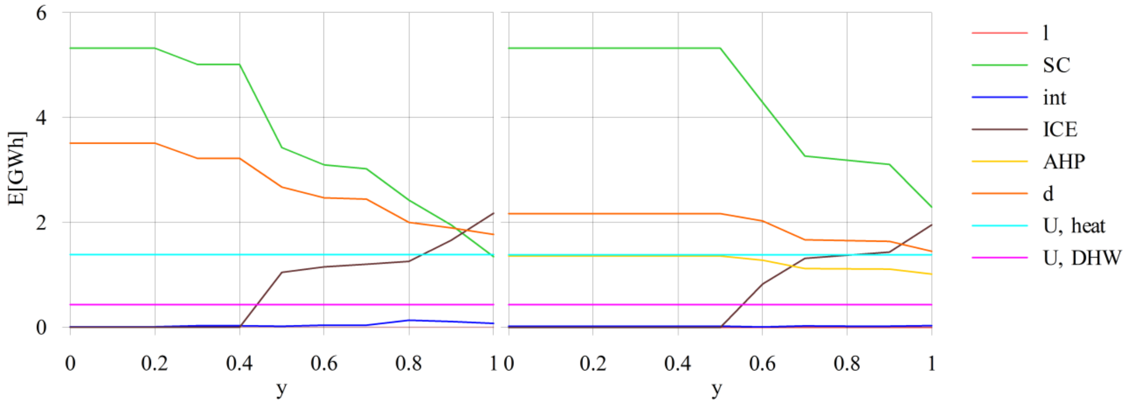

Fig. 11. Annual balance of the low temperature thermal energy for Case 1 (on the left)and Case 2 (on the right).

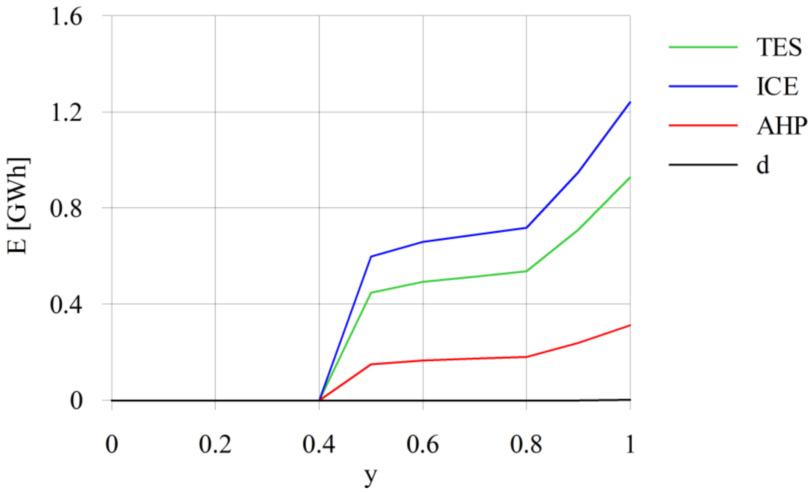

Fig. 12. Annual balance of the high temperature thermal energy for Case 1.

4.3. Costs

Trends in Fig. 13,14,15 are referred to the costs analysis, showing the normalized[§] costs and revenues as a weight factor function.

About the investments costs (illustrated in Fig. 13), it's observed that the main contribution is referred to the solar collectors, that obviously decreases as the collectors area decreases, and, in Case 2, it results slightly greater in the whole *y* range due to the greater solar collectors area and the presence of the AHP also for low *y* values.

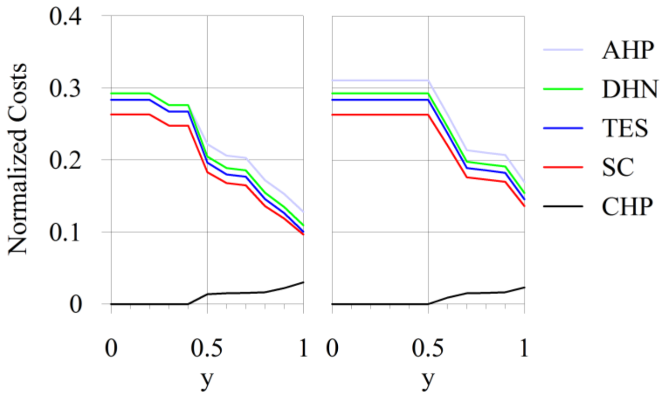

Fig. 13. Investment costs as a function of the weight factor (Case 1 left, Case 2 right).

Variable costs (Fig. 14) compensate this effect: Case 2 presents reductions of about 20% with respect of Case 1. Obviously, the ICE variable costs (comprehensive of fuel and maintenance) increases as the ICE power increases. About the integrations, the contribution of the electric energy integrated from the grid is relevant for the low y values and decreases significantly as the ICE size increases. Precisely,

[§] In all the following figures, the ordinates of each term are evaluated as the own contribution summed with that below (cumulated) and referred to the Ante Operam costs (normalized).

for low y values, it's observed that Case 1, due to the absence of the AHP, requires more electric energy integration for CAC feeding; thermal energy integrated through the auxiliary boiler is negligible for Case 1 and null for Case 2.

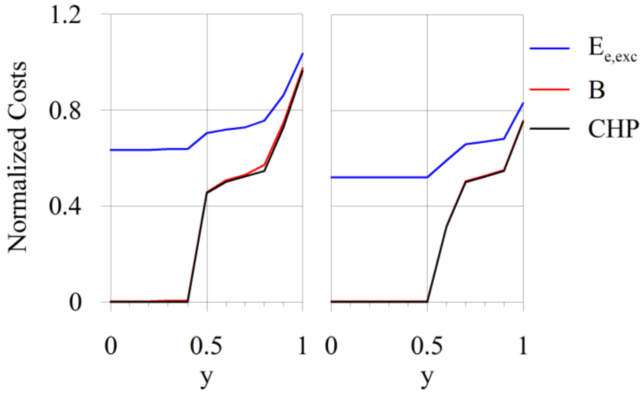

Fig. 14. Variable costs as a function of the weight factor (Case 1 left, Case 2 right).

All the previous aspects justify the more economic convenience of Case 2 compared to Case 1, even if for the latter the revenues (considered with negative sign) results greater (Fig. 15). Here the main contributions, for both the Cases, are represented by the electric energy sold to the grid and the tax exemptions of the fuel for the CHP feeding. As already observed, Case 1 is characterized by a greater CHP power that increases the redundance of electric energy that can be sold and the thermal energy fraction cogenerated that implies more tax exemption. Anyway, the benefits do not compensate the greater variable costs of Case 1.

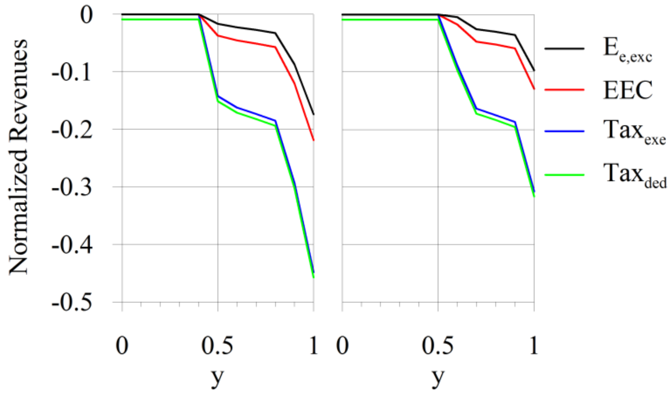

Fig. 15. Revenues as a function of the weight factor (Case 1 left, Case 2 right).

5. Conclusion

The work proposes a mathematical model for the optimization of alternative energy supply systems based on CCHP integrated with solar plants and applied to the residential sector. These systems are characterized by a conflict between the minimization of costs and of CO_2 emissions, mainly due to the capital costs contribution and a suitable multi-objective optimization should be formulated. The model allows for the costs and the CO_2 emissions minimization, linked through a weight factor, and it's based on a simple mathematical formulation but on an engineering effective approach. The plant layout is based on an ICE that produces the electric energy and whose heat is sent to a thermal energy storage, where low temperature solar collectors system gives a further contribution. The optimization has been referred to two plants layout schemes. In the first, the AHP is directly fed by the high temperature engine exhaust gases; in the second, the AHP thermal source is the TES with an higher system integration level. Referring to the usual energy supply system, for the first Case, a mean reduction of both costs and CO_2 emissions of about 20% is obtained. For the second Case, costs and CO_2 emissions reduces of 25% and 32%, respectively. These results show a more convenient condition if the AHP is connected to the TES despite the lower thermal energy temperature of the AHP thermal source leads to lower AHP COP values. This reveals that a higher level of integration among the system components can give a better global effectiveness on both costs and emissions reduction.

Nomenclature

Symbols
A surface
E energy
F objective function
P power
T temperature
V volume
c specific heat
m mass
t time
x independent variable of the objective function
y weight factor in the objective function

Subscripts
aux auxiliary
C costs
Ob objective
U user
c cooling
d dissipated
ded deduction
e electric
exe exemption
exc exchanged
heat heating
ht high temperature
int integrated
l lost
lt low temperature
pur purchased
s sold

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