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## A model for the optimal management of a CCHP plant

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### Abstract

Distributed Generation can give a relevant contribution to the reduction of the primary energy needs and consequently of the green-house gases emissions. Moreover, it can stimulate the diffusion of renewable energy exploitation technologies through integration. This is widely relevant for the household sector, where energy is required in several forms: electric, heating, cooling. In this paper an energy system optimization model is proposed. The model optimizes the components size and their operating conditions during the day. The energy system is composed of a combined cooling, heating and power system, based on an internal combustion engine and an absorption heat pump integrated with solar thermal and photovoltaic systems. The model minimizes the costs and/or the CO<sub>2</sub> emissions and the results reveal that the engine variable operating conditions are more effective than the steady state.

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*Keywords:* CCHP; Photovoltaic; Solar Collectors; Integration; Optimal management.

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### 1. Introduction

Since 2010 the Energy Technology Perspectives (ETP) published by the International Energy Agency (IEA), has tried to give a long term forecast, up to 2050, for the equilibrium between the world energy needs and the primary sources exploitation [1]. This equilibrium must give an answer to the challenge of facing the energy demands in a sustainable environmental way. In 2005, the Green House Gases (GHG) emissions were 28 Gt, in a Business As Usual (BAU) scenario, and following this trend, the atmospheric temperature in 2050 would increase of 6°C [2].

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With the aim to contain this temperature increase within 2°C, the GHG emissions during the period 2010-2050 must be halved compared to the reference value. The Agency proposes a roadmap indicating several topics where Renewable Energy Sources (RES) and more effective energy conversion technologies play a crucial role.

It's well known that Distributed Generation (DG), based on RES and fossil fuels also, does give a significant contribution in this context [3]. In fact, DG allows for the integration among several technologies where the synergy of cogeneration (Combined Heating and Power – CHP), trigeneration (Combined Cooling Heating and Power – CCHP), RES exploitation and energy storage is enhanced [4], due to its greater convenience in terms of primary energy saving, so also in terms of minor costs and avoided emissions, if compared to the traditional separate way of energy supply [5,6]. This is true especially for the residential sector [7,8], where the energy demand for space heating and cooling and domestic hot water constitutes the greatest contribution in most of the European countries [9], and in a small scale, allowing the best integration with Renewable Energy Sources [10,11], diffusely available on the territory, like the solar one [12].

These benefits, however, are strictly subjected to an adequate definition of both the CHP/CCHP nominal power and its operating conditions management.

The first aspect is related to the large investments required for the CHP/CCHP system that determine uncertainties about the payback period, even if the primary energy sources are exploited in a more effective way. In fact, in particular for mixed-resources systems, there's still a discrepancy between the capital costs, that, remaining high discourage their penetration, and the lower emissions rates compared to centralized power plants, which don't offer economic incentives to internalize.

About the second aspect, generally, cogeneration systems are operated at fixed point because maximum efficiency values compete to nominal conditions, but Internal Combustion Engines (ICE)<sup>1</sup> fueled by natural gas could offer acceptable efficiency values operating at partial loads, even up to 50% of the nominal one [13], providing a greater level of flexibility in the plant operation. In fact, if the electricity distribution network behaves like an infinite capacity able to receive the surplus production and to yield the gaps, all obviously exposed to the pricing in force, on the other hand for the thermal energy, its production must necessarily be synchronous with the needs and surplus of energy are inevitably dissipated, especially if accumulation systems are not present. This is true in particular for the network integration of Distributed Generation based on RES, where long term thermal storage can add more options to the operation of District Heating Network (DHN) [14], being strongly influenced by the amount of the energy expected from the RES and the ability of the power system to balance between power generation and consumption [15].

So, a *load follower* operation mode may result more convenient rather than a compensation via supply infrastructure [16]. This is true especially for the residential sector, where the energy needs variations during the day and the seasons are significant [17]. Moreover, it's well known that electric energy produced by DG sets a new kind of troubles to electric grids. The distribution network was built with the aim to transfer energy from the production sites to the end-users, and the reduction of electric energy exchanges between the local production systems and the grid (energy selling and purchasing) is worthy of attention [18-21]. A robust operation strategy, able to return the set points for the optimal matching between the plant sizing and the energy loads, that fluctuate widely with time, is a key aspect. The optimal operation management of these systems must consider, on a multi-hourly basis, both the temporal evolution of the users energy demands and the electricity tariffs, being strongly influenced by uncertain economic factors of the energy market [22]. For all these reasons, the seeking of a compromise solution requires an adequate technique based on multi-criteria methods able to reveal how both to design (i.e. configure and size) and to dispatch (i.e. management) at minimum economic and environmental costs.

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<sup>1</sup> This kind of prime mover is the most suitable for application in the residential sector.

Similarly focused researches in literature apply different approaches. The main are the Thermo-dynamic [23], integrating often Thermo-Economics [24-26], through often dynamic programming methods [27], and pinch-analysis [28], or directly mathematical programming, able to handle trade-offs more efficiently, e.g. in Mixed Integer Linear/Non-Linear Programming [14, 29-30]. Anyway, they are mostly referred to large and complex industrial facilities, and mainly to the optimal design aspect, while a combined design and energy dispatching optimization [31-34] is rather infrequent.

Expecting, by a variable operating mode, a better profit with respect to the fixed point one, already studied by authors through a procedure easily applicable in a small scale [35,36], this work enlarges this method introducing the optimal management, in the residential sector, of a plant considered as a retrofit of an existing one based on the separate production. It's constituted by a CCHP, based on an Internal Combustion Engine and an Absorption Heat Pump (AHP), a low temperature solar collectors plant, integrated to them through a Thermal Energy Storage (TES), and of a Photovoltaic (PV) system. The model, minimizing both CO<sub>2</sub> emissions and costs, conducts a multi-objective optimization that returns the plant devices sizes and, also, the ICE set points. The model allows for the engine to operate at electric variable load, and also with a varying level of temporal detail, considering several hour intervals during the week, starting from steady state conditions up to hourly load variations. The model has been applied to a set of 360 apartments located in the North of Italy.

## Nomenclature

### Symbols

$\Delta t_{ICE}$	time interval	inv	investment
B	Boiler	m	maintenance
C	Costs	o	operating
F	Function	p	peak
I	Investment	pur	purchased
P	Power	s	sold
R	Returns		
U	user		
V	Volume of gas		
c	unit cost		
d	discount rate		
es	other costs escalation		
in	energy vectors inflation		
l	capital cost rate		
t	time		
v	life span		
x	weight factor		
y	independent variable in the objective function		

### Acronyms

AO	Ante Operam
AHP	Absorption Heat Pump
CAC	Compression Air Conditioning
CHP	Combined Heat and Power
CCHP	Combined Cooling Heating and Power
DG	Distributed Generation
DHN	District Heating Network
EAC	Equivalent Annual Cost
EEC	Energy Efficiency Credits
EF	Emission Factor
GHG	Green House Gases
HE	Heat Exchanger
HEC	High Efficiency Cogeneration
ICE	Internal Combustion Engine
PES	Primary Energy Saving
PO	Post Operam
PV	Photovoltaic
RES	Renewable Energy Sources
SC	Solar Collectors
TES	Thermal Energy Storage

### Subscripts

Ob	Objective
a	active
c	cooling
ded	deductions
e	electrical
exe	exemption
g	gas
i	system component

## 2. Plant modeling

The model is referred to the plant layout shown in Fig. 1, where the energy flows among the devices are highlighted with different colours. The thermal energy flows, red lines, are exchanged among: TES, SC, B, ICE, AHP and the end user. The electric energy, yellow lines, is produced by the alternator coupled with the ICE and by the PV, and feeds the end-user and, eventually, the CAC for the chilling needs. About the latter, cooling energy flows are represented by blue lines and the main contribution are due to the AHP. The electric energy flows are completed with the grid exchanges.

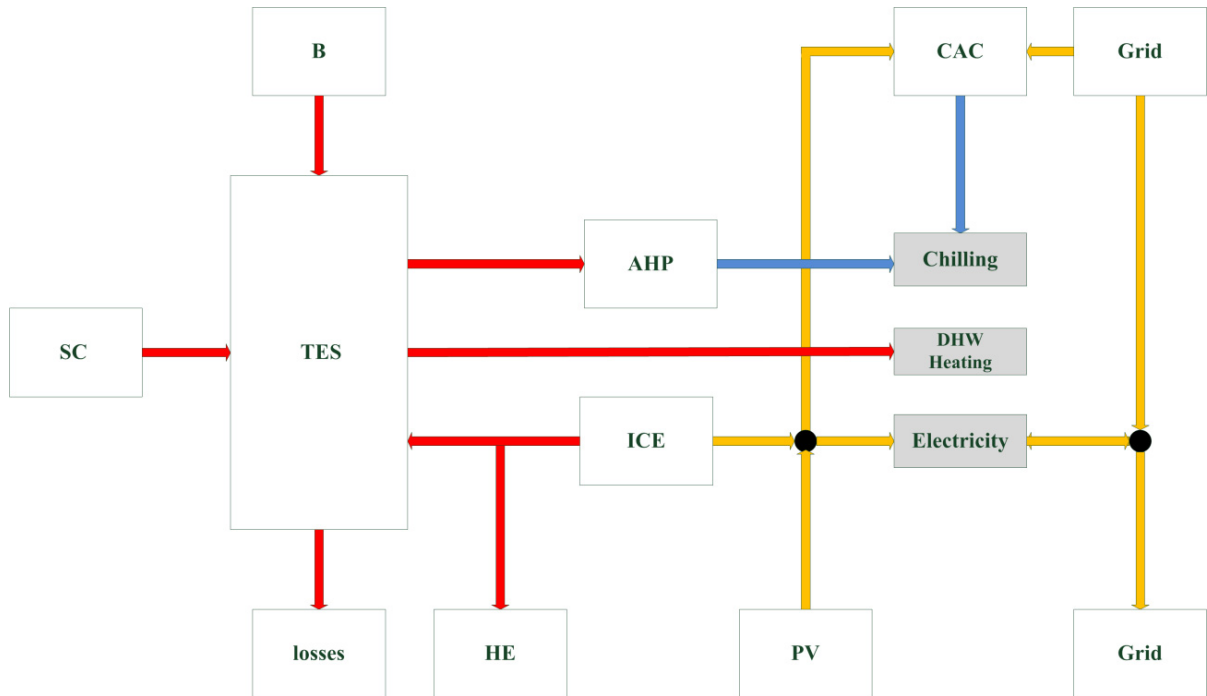


Fig. 1. System superstructure. Grey boxes represent the user needs.

The model:

- 1- Evaluates the costs and the CO<sub>2</sub> emissions related to the end user needs in the Ante Operam (AO) situation;
- 2- Sets the nominal and off-design components characteristics in terms of unit costs and part-load efficiency;
- 3- Sets the TES constraints for the stored thermal energy stability (periodic thermal regime and maximum fluid temperature swings according to Eq. (1));

$$\max(T_{TES}(t)) - \min(T_{TES}(t)) \leq \Delta T_{TES} \quad (1)$$

Evaluates investment, maintenance, rating costs of the new solution, that are normalized with respect to the AO condition,  $F_C$ ;

- 4- Calculates the CO<sub>2</sub> emissions of the new solution, that are normalized with respect to the AO condition,  $F_{CO_2}$ ;
- 5- Combines the two contributions of previous point 4 and 5 through a weight factor,  $x$ , variable between 0 (emissions optimization) and 1 (costs optimization) according to Eq. (2), where  $y_i$  are the ICE, PV, SC, AHP sizes and the engine set points;

- 6- Minimizes the function of Eq. (2) through an algorithm for the minimum of constrained nonlinear multivariable function of the Matlab© package.

$$F_{Ob}(y_i) = x \cdot F_C(y_i) + (1-x) \cdot F_{CO_2}(y_i) \quad (2)$$

As already mentioned in the previous point 6, the ICE set points are among the optimization variables. The model allows for the ICE load variation from the steady state condition (constant load), up to continuously transient conditions (ICE load varying every hour).

### 2.1. Costs

The costs composing  $F_C$  are defined, for the Post Operam (PO), according to Eq. (3),

$$C = (C_{inv} + C_o) - C_a \quad (3)$$

where:

$C_{inv}$  is given by Eq. (4), where the investment cost of each component  $i$  is multiplied by the *capital recovery factor*;

$$C_{inv} = \frac{l \cdot (1+l)^y}{(1+l)^y - 1} * \sum_i I(i) \quad (4)$$

$C_o$  is defined by the sum of costs for energy carriers (fuel required by ICE and B, and electricity) and for maintenance (of the specific component), each depending on the time interval assumed, according to Eq.(5).

$$C_o = \sum (E_{pur}(t) \cdot c_{e,pur}) + V(t) \cdot c_g + \sum_i (c_{m,a}(i,t)) \quad (5)$$

$C_a$  is defined by the sum of all returns: selling of the electricity to the grid, selling of Energy Efficiency Certificates (EEC), tax exemption applied to the portion of the gas required by ICE (if it respects the High Efficiency Cogeneration conditions [37], evaluated through the Primary Energy Saving, PES), tax deductions for installation of SC, according to Eq. (6).

$$C_a = \sum (E_s(t) \cdot c_{e,s}) + R_{EEC}(t) + R_{exe} + R_{ded} \quad (6)$$

All costs are evaluated as Equivalent Annual Costs (EAC) in order to bring the analysis to an average year.

### 2.2. CO<sub>2</sub> emissions

The CO<sub>2</sub> emissions for both AO and PO conditions have been evaluated according to a standard approach (i.e. considering only the in situ energy conversion and not the entire life cycle for the production and transmission of the energy vectors) [38].

### 3. Model application

#### 3.1. End-user energy needs

The size and the operating conditions of the system in Fig. (1) have been optimized for the energy needs of a residential area of eighteen two levels buildings for a total of 360 apartments, 50 m<sup>2</sup> each one, connected through DHN.

The house energy needs are for space heating/cooling, Domestic Hot Water (DHW) and electricity. The energy demands, obtained using a software for the energy certification, starting from data available in literature [39], are shown in Fig. (2), varying during the day.

For what concerns the electric and DHW needs, the mean values averaged on a year basis, while the maximum heating and cooling demands are referred to February and July, respectively.

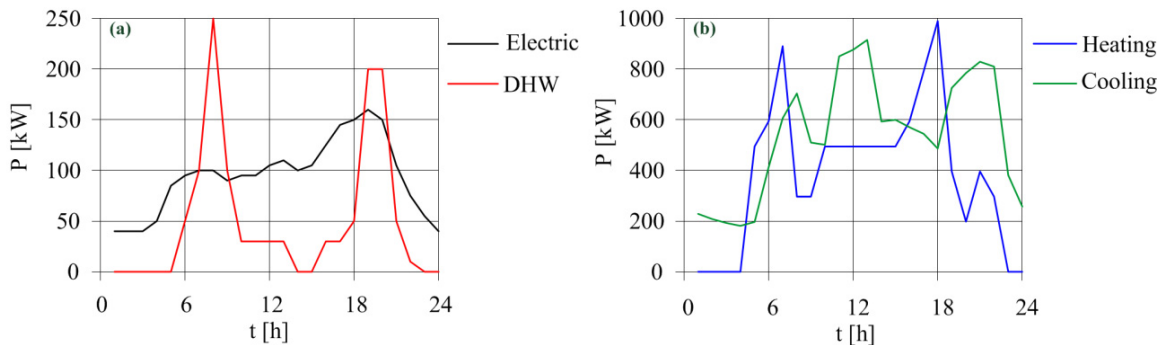


Fig. 2. (a) User electric and DHW needs; (b) User heating and cooling needs.

#### 3.2. Plant devices assumptions

The ICE is spark ignited and fed by natural gas. The thermal energy is recovered at low temperature from the engine cooling and lubrication circuits and at high temperature from the exhaust gases. Both this two contributions enter the TES.

Engine efficiency has been considered variable with the engine nominal power and load.

The investment cost per unit of power have been considered variable with size and, for example, for an electric power equal to 150 kW, the unit cost is 1000 €/kW. The maintenance, lubrication and ancillary costs are proportional to the electric energy production and are equal to 30 €/MWh.

A single stage and lithium bromide AHP has been considered, with a COP equal to 0.65, and, as for the ICE, the investment cost depends on the size (for example, for a cooling power equal to 250 kW, the unit cost is 200 €/kW).

The auxiliary B and CAC for heating and cooling integrations have an efficiency equal to 0.85 and a COP equal to 3.2, respectively.

The TES is based on water and is modeled according to a *lumped parameter* approach; the cost for unit volume depends on the thermal insulation level and, for this application, a global walls transmittance of 0.4 W/m<sup>2</sup>K, which corresponds 150 €/m<sup>3</sup>, has been assumed.

For the DHN has been assumed a cost of 1 €/m<sup>3</sup> of air-conditioned volume.

SC are *evacuated tube* type with a cost for unit area equal to 300 €/m<sup>2</sup>, and the efficiency is variable with the external air temperature.

The PV system is *polycrystalline silicon* type with a cost equal to 2000 €/kW<sub>p</sub>, comprehensive of balance of plant.

According to the building roof surface available, the total area occupied by SC and PV has been assumed equal to 5000 m<sup>2</sup>.

### 3.3. Tariffs and rates, other assumptions

Table 1 shows the values assumed, according to the current Italian market, for the energy vectors costs, the discount rates and the Emission Factors (EF) for the CO<sub>2</sub> mass calculation.

Table 1. Energy vectors costs, discount rates, CO<sub>2</sub>EF.

Parameter	Value
$C_g$	0.455 €/m <sup>3</sup>
$C_{e,pur}$	0.21 €/kWh
$C_{e,s}$	0.09 €/kWh
$v$	20 years
$in$	3 %
$es$	2 %
$d$	7 %
$l$	6 %
$EF_g$	0.202 kg <sub>CO2</sub> /kWh
$EF_e$	0.482 kg <sub>CO2</sub> /kWh

Solar radiation has been evaluated on an hourly basis, according to the procedure of the Italian regulation [40] and modified as outlined in [41, 42].

## 4. Results

The most important optimization parameter for the proposed model is the time interval for ICE load variation  $\Delta h_{ICE}$ . In the present analysis, it's expressed in hours and it has been assumed equal to 24 (representing the fixed point ICE operating condition), 12, 6, 4, 2, 1. In the latter case, the ICE time interval management is the same of the end-user energy needs time variation availability. As already observed in Eq. (2), the  $x$  parameter represents the relative weight of the  $F_C$  (minimized when  $x=1$ ) and the  $F_{CO_2}$  (minimized when  $x=0$ ). The variation of the  $x$  parameter causes a trade-off behavior because at the maximum costs reduction corresponds the minimum CO<sub>2</sub> reduction, and vice versa. These trade-offs, also known as Pareto fronts, are shown in Fig. 3. Considering the definition of the costs and CO<sub>2</sub> emissions functions on the plane of Fig. 3 the point with coordinate (1,1) represents the AO situation. For low  $x$  values, this parameter does not have any influence, leading to about 30% of costs reduction and 60% CO<sub>2</sub> emissions reduction. As  $x$  increases, its influence becomes very important and the curves show very different trends. For a given costs reduction, the CO<sub>2</sub> emissions reduction increases as  $\Delta h_{ICE}$  decreases. For  $x=1$ , the engine fixed point operating condition gives a costs reduction of about 35% with the emissions reduction of 42%. For  $\Delta h_{ICE}=1$ , the costs reduction is 38% and the emissions reduction is about 50%.

Figures 4,6,7 show the sizes of the devices influencing the optimization as a function of  $x$ :  $P_{e,ICE}$ ,  $A_{PV}$ ,  $A_{SC}$ ,  $P_{AHP}$ , respectively.

It can be observed the low influence of the  $x$  parameter for values up to 0.3, and this aspect justifies the overlapping of the trade-off curves of Fig. 3. For  $x>0.3$ , the nominal engine power increases and, for  $\Delta h_{ICE}=1$ , it reaches the maximum value equal to 150 kW at  $x=0.6$ . For greater values of  $\Delta h_{ICE}$ , the maximum engine power is obtained for greater values as  $\Delta h_{ICE}$  increases. The nominal minimum engine power value is in  $x=1$ , about 80 kW for  $\Delta h_{ICE}=24$ . The strong difference is between  $\Delta h_{ICE}=1$  and the engine fixed point operating conditions are due to the lower engine contribution at part load: in this way, for a given electric energy produced by ICE, the nominal power

must be greater than that for the fixed point. This is justified observing Fig. 5 representing the electric energy annual balance for  $x=1$ , where the ICE contribution results almost constant with  $\Delta h_{ICE}$ .

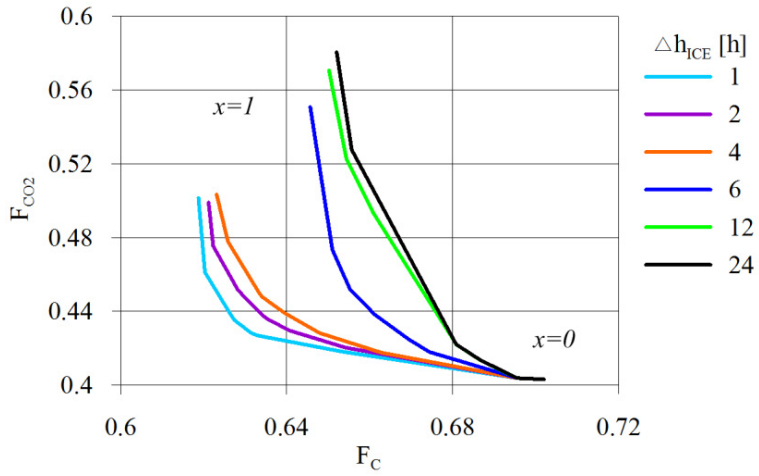


Fig. 3. Trade-off fronts.

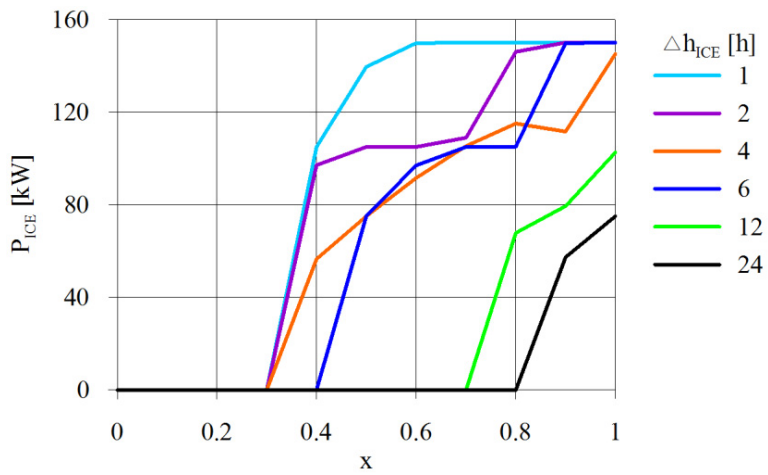


Fig. 4. ICE nominal power as a function of the weight factor.

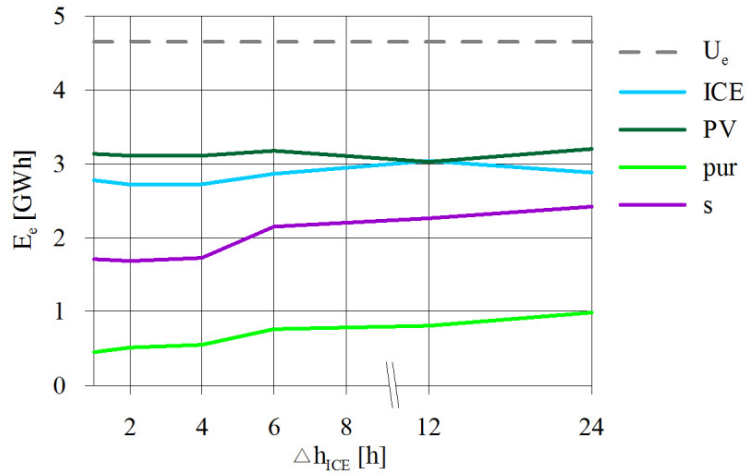


Fig. 5. Electric energy balance.

From the same figure it's evident that, if  $\Delta h_{ICE}$  reduces, the electric energy exchanged with the grid (both sold and purchased) decreases limiting the interactions with the network and the relative overcharge with benefits for the electric system. Again, from Fig. 5, also  $E_{e,PV}$  results almost constant. This means that the PV area for  $x=1$  varies very slightly with  $\Delta h_{ICE}$ , as shown in Fig. 6 which shows the  $A_{PV}$  trends as a function of  $x$  for all the  $\Delta h_{ICE}$  considered. Generally,  $A_{PV}$  increases as  $x$  increases, more rapidly for low  $\Delta h_{ICE}$  values.

For what concerns  $A_{SC}$ , shown in Fig. 7, its trend results opposite to  $A_{PV}$ , being the  $A_{PV}$  and  $A_{SC}$  sum equal to the  $5000 \text{ m}^2$  the upper bound set for the optimization.

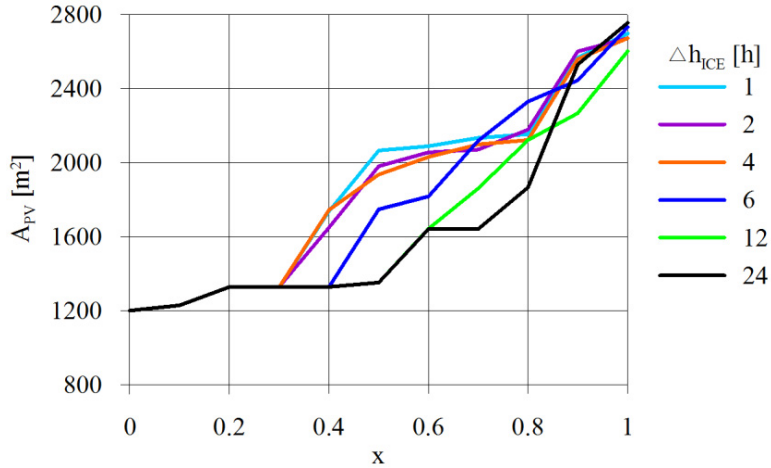


Fig. 6. PV area trends as a function of the weight factor.

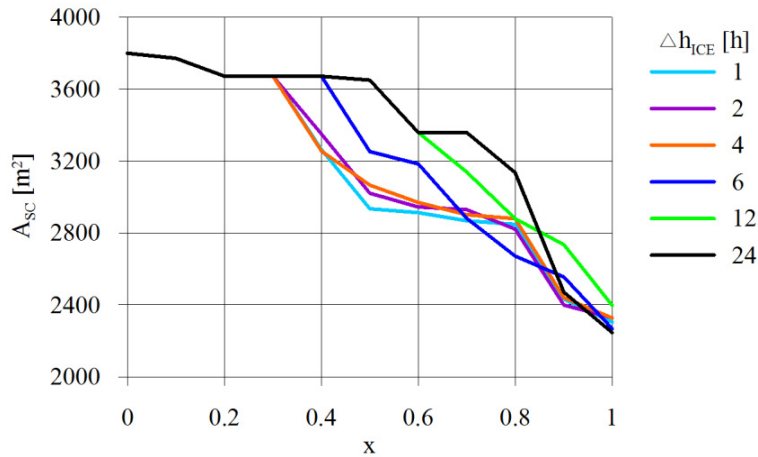


Fig. 7. SC area trends as a function of the weight factor.

The AHP power ranges between 260 kW and 300 kW for every value of  $x$  and  $\Delta h_{ICE}$  revealing a poor importance as optimization variable.

About the TES volume, it must be observed that its size is not an optimization variable, because, as already mentioned, it's subject to the two energy constraints: keep a periodic thermal regime able to restore the same fluid temperature at the beginning of the day, and control the temperature swings. For this application, the mean TES fluid temperature has been set equal to 70°C and the maximum temperature swing is imposed equal to 10°C. The TES volume is mainly influenced by the SC area and the ICE power and its maximum value is 600 m<sup>3</sup> for  $x=0$ , independently by the  $\Delta h_{ICE}$  parameter.

As observed from Fig. 3, the maximum costs advantage ( $x=1$ ) increases if  $\Delta h_{ICE}$  decreases. This is due to a greater flexibility in the ICE management, that allows for a wider capability of the system to integrate the several technologies main related to the electric energy production. Fig. 8 shows instantaneous electric power produced by the ICE for the  $\Delta h_{ICE}$  here considered along the standard day. In the same figure the instantaneous electric need is also plotted. From the figure it's clear that, if the engine load is controlled through short time intervals, the model suggests to switch off the engine during the central hours of the day, even if the end user need are significant. The engine shutting down period goes from about 9 a.m. to 4 p.m. This aspect is clearly shown from the results of Fig. 9, where the hourly electric power balances are illustrated for two typical days referred to July (a) and to February (b), representative of the hottest and coldest atmospheric environmental conditions. In this time period the contribution of the PV electric production is significant, and more relevant for the costs optimization if compared to the electric energy produced by the ICE. Moreover, for the July day, the electric energy need for cooling integration through CAC is relevant and it can be observed that to partially satisfy it, integrations from the grid are necessary during the engine shutting down period, when the solar energy is available. During the evening, the ICE covers the electric load and the air cooling is satisfied through electric energy integration. This is due to the lower thermal energy available from the TES to feed the AHP. This does not mean that electric energy integration is more convenient with respect to the self-production, because the optimization refers to the whole integrated system. The electric energy sold to the grid is almost negligible.

For the winter typical day (b), the time period of the contribution is obviously shorter<sup>2</sup>. For this day, during the central hours, being the electrical needs lower than the same in the Summer day, no energy integration is required, and the surplus energy is entirely sold to the grid.

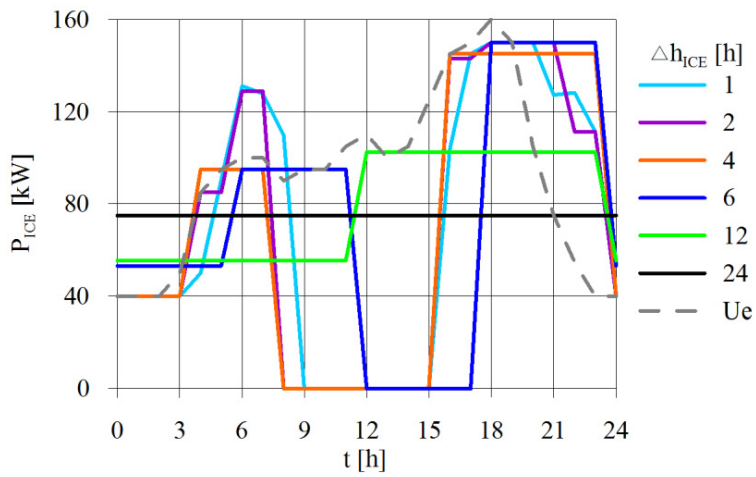


Fig. 8. ICE daily variations.

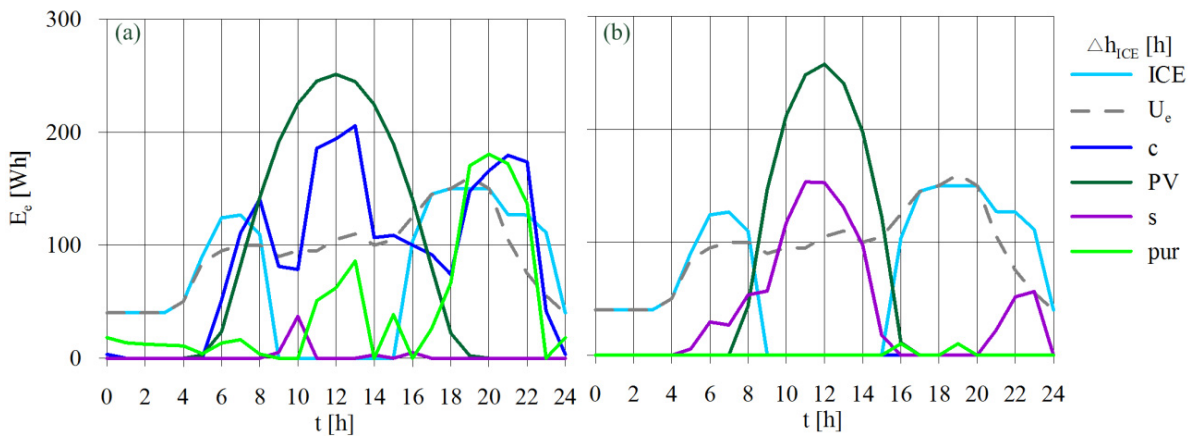


Fig. 9. Daily electric energy balance for a summer day (a) and for a winter day (b).

<sup>2</sup> In Fig. 9, the PV power peak is slightly higher for the winter months. This is due to the PV arrays tilt angle, which has been optimized in order to maximize the PV energy production. The resulting tilt angle maximizes the peak radiation along the winter period.

## Conclusions

A mathematical model for the optimal design and management of a CCHP system, composed of an internal combustion engine and an absorption heat pump integrated with solar energy conversion technologies is presented. The model is user-needs oriented, and is easily applicable to small scale clusters in the residential sector.

The model has been applied to a residential complex, composed of 360 apartments connected through district heating network, and defines the devices sizes and their operating conditions. In the optimization process the ICE load has been considered variable analyzing several time intervals. The model application has been revealing that the best solution comes from the system optimization, and not from the single device optimization, where the single component could not be operated at its own nominal conditions. The optimization has been conceived on a multi-objective basis, minimizing the costs and the GHG emission. The best costs reduction obtained is 35% and the best GHG reduction obtained is 60%.

As the engine set-point time variation reduces, the whole system performance increases. This is due to a more effective energy exploitation of the system devices and to the reduction of the electric energy grid interactions, leading the system toward an energy island configuration and reaching, in this way, the core goal of the distributed generation model of energy.

## References

- [1] IEA, *Energy Technology Perspectives - Scenarios & Strategies to 2050*, <http://www.iea.org>, 2010.
- [2] IEA, *Energy Technology Perspectives - Harnessing Electricity's potential*, <http://www.iea.org>, 2014.
- [3] W. S. Tan et al., *Optimal distributed renewable generation planning: A review of different approaches*, *Renewable and Sustainable Energy Reviews*, Vol. 18, pp. 626–645, 2013.
- [4] A. Schäfer et al., *Optimization of Thermal Energy Storage Systems in Distributed Generation Systems*, *Z Energiewirtschaft*, Vol. 36, pp. 135–145, 2012.
- [5] A. Verbruggen, *The merit of cogeneration: Measuring and rewarding performance*, *Energy Policy*, Vol. 36, pp. 3059–3066, 2008.
- [6] G. Chicco et al., *Distributed multi-generation: A comprehensive view*, *Renewable and Sustainable Energy Reviews*, Vol. 13, pp. 535–551, 2009.
- [7] H. Lund et al., *The role of district heating in future renewable energy systems*, *Energy* Vol. 35 pp 1381–1390, 2010.
- [8] J. F. Belmonte et al., *Trigeneration with micro-CHP and absorption cooling for the residential sector in Mediterranean climate*, 2nd European Conference on Polygeneration, Tarragona, Spain, 30th March-1st April 2011.
- [9] Enerdata, *Energy Efficiency Trends in Buildings in the EU*, Lessons from the ODYSSEE MURE Project, 2012.
- [10] N. Raja et al., *A review of renewable energy based cogeneration technologies*, *Renewable and Sustainable Energy Reviews*, Vol. 15, pp. 3640–3648, 2011.
- [11] Karl Sperling et al., *End-use energy savings and district heating expansion in a local renewable energy system—A short-term perspective*, *Applied Energy*, Vol. 92, pp. 831–842, 2012.
- [12] A. G. Hestnes, *Building Integration of Solar Energy Systems*, *Solar Energy*, Vol. 67, Nos. 4–6, pp. 181–187, 1999.
- [13] J.B. Heywood, *Internal Combustion Engine fundamentals*, McGraw-Hill Book Company, 1988.
- [14] T. M. Tveit et al., *Multi-period MINLP model for optimizing operation and structural changes to CHP plants in district heating networks with long-term thermal storage*, *Energy Conversion and Management*, Vol. 50 pp. 639–647, 2009.
- [15] P.S. Georgilakis, *State-of-the-art of decision support systems for the choice of renewable energy sources for energy supply in isolated region*, *International Journal of Distributed Energy Resources*, Vol. 2, No. 2, pp. 129–150, 2006.
- [16] C.Y. Zheng et al., *A novel operation strategy for CCHP systems based on minimum distance*, *Applied Energy*, Vol. 128, pp. 325–335, 2014.
- [17] E. Pohl et al., *A method to determine primary energy savings of CHP plants considering plant-side and demand-side characteristics*, *Applied Energy* Vol. 113, pp. 287–293, 2014.
- [18] A. Etxeberria et al., *Hybrid Energy Storage Systems for Renewable Energy Sources Integration in Microgrids: A Review*, IEEE-IPEC, 2010.
- [19] D. Dustegor et al., *A Distributed Fault Protection Method for Power Grid with High Penetration of Renewable Energy Sources*, IEEE 2011.

- [20] Hartono BS et al., *Review of Microgrid Technology*, IEEE 2013.
- [21] F.W. Fuchs et al., *Research Laboratory for Grid Integration of Distributed Renewable Energy Resources-Design and Realization*, IEEE 2012.
- [22] K. Mark et al., *Decision support tools for advanced energy management*, Energy Vol. 33, pp. 858–873, 2008.
- [23] E. D. Rogdakis et al., *Thermodynamic analysis and experimental investigation of a Solo V161 Stirling cogeneration unit*, Energy, Vol. 45, pp. 503–511, 2012.
- [24] M. A. Lozano et al., *Thermoeconomic Cost Analysis of Central Solar Heating Plants Combined With Seasonal Storage*, IMECE 2010.
- [25] D. Tempesti et al., *Thermoeconomic assessment of a micro CHP system fuelled by geothermal and solar energy*, Energy Vol. 58, pp. 45-51, 2013.
- [26] V. Verda et al., *Thermoeconomic approach for the analysis of control system of energy plants*, Energy, Vol. 41, pp. 38–47, 2012.
- [27] V. Marano et al., *Application of dynamic programming to the optimal management of a hybrid power plant with wind turbines, photovoltaic panels and compressed air energy storage*, Applied Energy, Vol. 97, pp. 849–859, 2012.
- [28] P. S. Varbanov et al., *Total Site targeting with process specific minimum temperature difference ( $\Delta T_{min}$ )*, Energy, Vol. 44, pp. 20–28, 2012.
- [29] W. Gu et al., *Modeling, planning and optimal energy management of combined cooling, heating and power microgrid: A review*, Vol. 54, pp. 26–37, 2014.
- [30] K. A. Pruitt et al., *Optimal design and dispatch of Distributed Generation Systems*, Argonne National Laboratory, 2012.
- [31] M.A. Lozano et al., *Operational strategy and marginal costs in simple trigeneration systems*, Energy Vol. 34, pp. 2001–2008, 2009.
- [32] K.C. Kavvadias et al., *Design of a combined heating, cooling and power system: Sizing, operation strategy selection and parametric analysis*, Energy Conversion and Management Vol. 51, pp. 833–845, 2010.
- [33] X.Q. Kong et al., *Optimal operation of a micro-combined cooling, heating and power system driven by a gas engine*, Energy Conversion and Management Vol. 50, pp. 530–538, 2009.
- [34] A. L. Facci et al., *Optimization of CHCP (combined heat power and cooling) systems operation strategy using dynamic programming*, Energy Procedia, Vol. 45, pp. 1295-1304, 2014.
- [35] M. Anatone, V. Panone, *Integration of CCHP and solar plants for household applications. A multiobjective optimization model*, presented at 2nd International Conference on Renewable Energy Research and Applications - Madrid, October 20-23 2013, published by.IEEE Xplore, pp. 499-504, 2013.
- [36] M. Anatone, V. Panone, *Optimization of integrated CCHP and solar plants following a multi-objective approach. An application to the household sector*, International Journal of Renewable Energy Research, Vol.4, No. 2, pp. 453-463, 2014.
- [37] Italian Ministry of Finance, Tax Law n. 44, 26th April 2012, *Conversion of law, with amendments, of Decree Law n. 16, 2nd March 2012 with urgent provisions relating to tax simplification, streamlining and strengthening of assessment procedures* (in italian), OJ n. 99, 28th April 2012.
- [38] Joint Research Centre, Covenant of Majors Office, *Guidelines How to Develop a Plan of Action for the Sustainable Energy - PAES*, EUR 24360 EN, 2010.
- [39] O. Perego et al., *Feasibility studies for cogeneration applications, status and perspectives of microcogeneration and estimation of the potential of district heating* (in italian), CESI Research, February 2009.
- [40] Italian regulatory body UNI 10349, *Heating and cooling of buildings-Climatic data* (in italian), 1994.
- [41] J. M. Gordon et al., *Stationary Statistics and Sequential Properties of Normal Beam Solar Radiation on Tilted Surfaces*, Solar Energy, Pergamon Press, Vol. 42, No.1, pp. 35-44, 1989.
- [42] R. Aguiar et al., *Statistical properties of hourly global radiation*, Solar Energy, vol. 48, pp. 157-167, 1992.