Optimal Design and Daily Operation of a Hybrid CHP System with Energy Storage

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Abstract:

The study and the optimization of single devices and plants, as well as of integrated systems among producers and users, must be performed considering the possibility of energy storage and of the conversion among different forms of energy in order to reach the best overall energetic and environmental performance. Small CHP distributed plants are particularly interested in these challenges, both in stand-alone and grid-connected configurations. Many different approaches have been proposed and applied to the optimization. In this paper, the optimal design and management strategy of a CHP system composed by a PV plant, a diesel CHP engine, a reversible heat pump and a boiler is studied. The possibility of storage by means of a hot reservoir, a cold reservoir, a pack of batteries, and a pumped hydro energy storage (PHES) is investigated. By applying a model based on the Particle Swarm Optimization (PSO), the size of the different devices and the operation strategy are simultaneously optimized. The most suitable hourly-based operation profile of the devices and the best management strategy of the energy storages were performed. The minimization of the overall costs was the problem's optimization target, while the main constrain was the fulfilment of the users' request of electricity, heat, cooling and drinking water.

Keywords:

Particle Swarm Theory; energy storage; hybrid system; cogeneration system, PV plant, batteries storage system.

1. Introduction

The increasing concern about the environmental impact of energy systems with the involvement in the Kyoto protocol for the greenhouse emissions reduction and the awareness about the importance of a responsible exploitation of energy sources explain the increasing diffusion and the promotion of the use of renewable sources and particularly of small plants and distributed generation. These plants permit the employment of low density distributed sources as biomass, wind, solar, mini-hydro and also contribute to reduce the transmission losses and the grid congestion problems. Moreover these plants are an interesting solution for insulated communities or communities looking for energetic self-sufficiency [1-2].

Their large use poses challenges and opportunities regarding their integration into energy supply systems; their planning and design must consider the environment itself, the needs of the overall electric system and the local needs of the place where they will be installed. In addition, the majority of plants based on renewable sources produce energy with a high variability and a considerable uncertainty about their capability of meeting the instant demand. One way to reduce this uncertainty, and, therefore, to guarantee the satisfaction of the user, without reducing the request, is the installation of an energy storage allowing the coupling adaptation of the production to the demand. That is why currently many different storage technologies are under development and improvement. Such systems have to play the important role of unifying, distributing and increasing the capacity of systems to alternative and renewable power generation [3-6].

In many cases, renewable energy plants are also integrated by devices fed by fossil fuels, mainly diesel internal combustion engines [7-10]. In this context, if there is also a thermal energy requirement, cogeneration is a further opportunity, leading to a better exploitation of fossil and/or renewable resources [11].

The complexity of hybrid systems makes very difficult their proper design and operation. For this reason, many different approaches have been proposed and applied to the optimization of these systems [12-15]. More generally, the concept of distributed multi generation approach is applied to systems where different energy vectors (electricity, heat, cooling power, hydrogen, water and so on) are produced, and distributed energy resources are used. In [13] a comprehensive review of many different approaches for the characterization, planning, evaluation and optimization of such systems is reported. The aim of the optimization problem is often the overall cost minimization: the optimal hourly, daily or annual operation strategy is evaluated to satisfy users' requirement.

In other cases, the main goal is the independence from fossil fuels or the lowest emissions. Note that in these cases, a certain grade of lack of availability must be often accepted.

In this paper, an original optimization model based on the Particle Swarm Optimization (PSO) theory is proposed and applied to a hybrid cogenerative system aimed at supplying electricity, heat, cooling power and water to an isolated tourist resort. It is composed by a diesel engine, a PV plant, a pack of batteries, a boiler, a reversible heat pump and a pumping device which can also be used as turbine (PAT). Water and hot and cold thermal storages have also been considered.

The novelty of the model is to deal with the simultaneous optimization of both sizes and hourly loads of each plant device. Many different constraints on the users' demand, the devices size, the operation strategy, the operation load can be easily managed. The resolution times are in the range of a few hours on a personal computer for a system with about 79 optimization variables, as for the case presented in this paper.

The paper is structured as follows: the case study is outlined in section 2. A detailed exposition of the model is proposed in Section 3 while results and conclusions are presented in Section 4 and 5 respectively.

2. System description

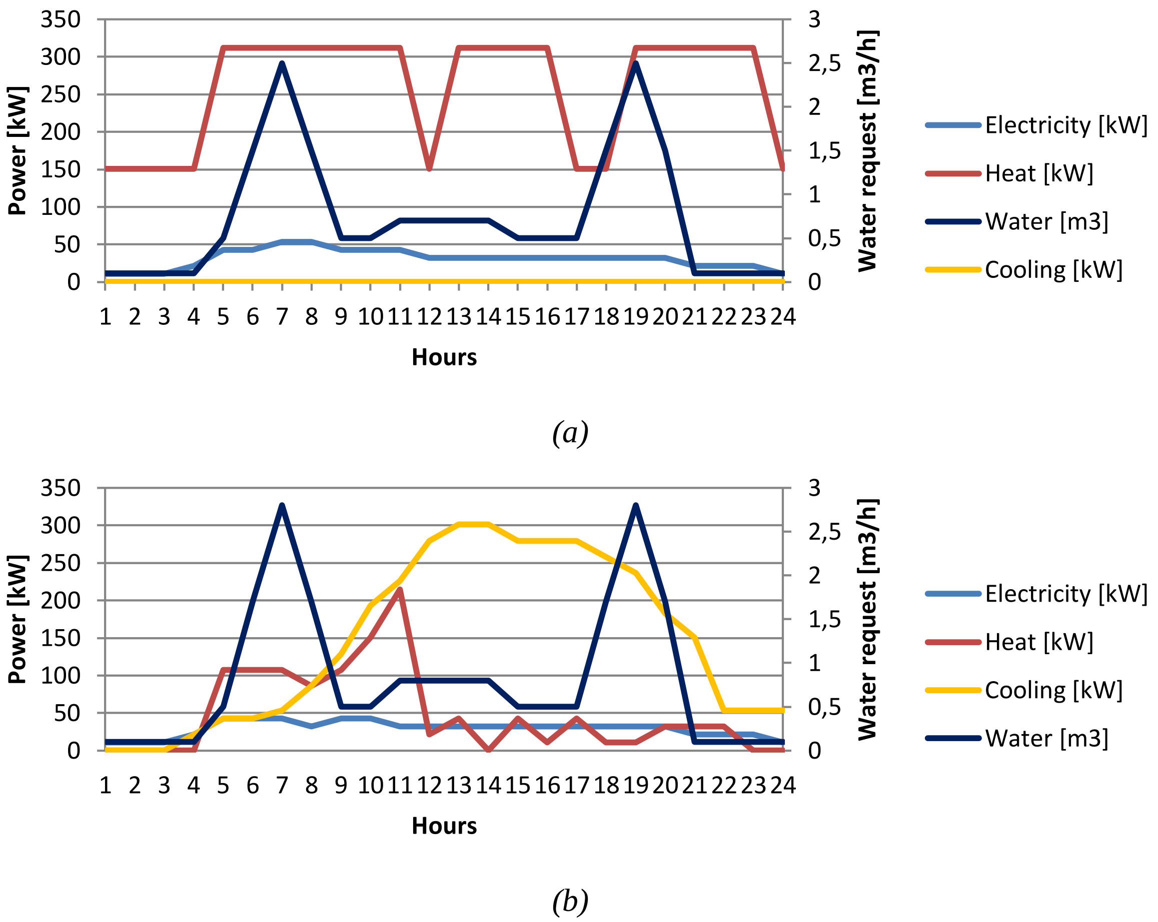
The case study is an isolated tourist resort in Northern Italy, located at about 1000 m above sea level, with an accommodation capacity of 170 people. The load requirements are electricity, heat, cooling and water as showed in the Fig. 1a and 1b for typical winter and summer days.

The annual energy and water requests are summarized in Table 1.

Table 1. Annual energy and water requirements

	Load requests			
	Electricity *[kWh]*	*Heat* *[kWh]*	*Cooling* *[kWh]*	*Water* *[m^3]*
Winter day	742	6192	0	17.6
Summer day	699	1161	3505	19.4

The plant is composed by a photovoltaic field (PV), a combined heat and power internal combustion engine (CHP), a boiler (B), a reversible heat pump (HP), a pump as turbine (PAT), a battery pack (BAT), an inverter (INV). For storage purposes there are a fuel storage, a hot storage, a cold storage, a lower water reservoir and an upper reservoir. The scheme in Fig. 2 summarizes the arrangement.



(a)

(b)

Fig. 1. Electricity, heat, cooling and water demand: a) in a typical winter day, b) in a typical summer day.

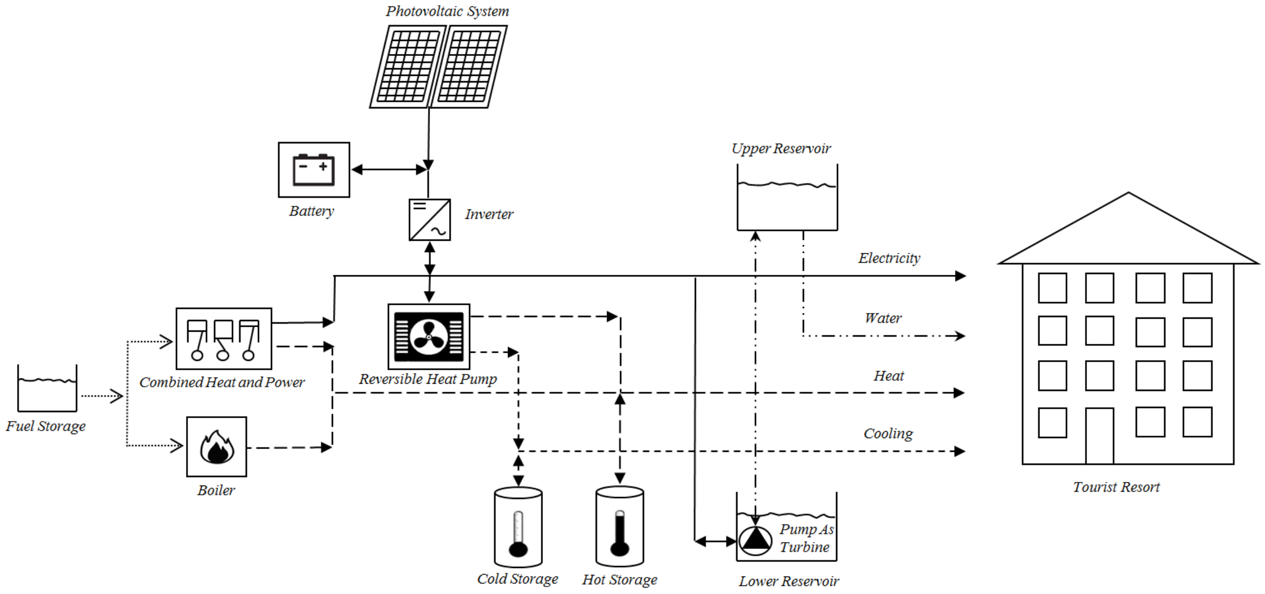


Fig. 2. Schematic of the hybrid system: solid lines represent electricity, dotted lines heat and cooling, and dashed lines water.

2. Model description

A detailed description of the model is reported in [15-16], but the model and the optimization technique have been further investigated. In this paper the main attention will be on the improvements of the model and the optimization technique.

2.1 - Components characteristics

For the photovoltaic system the data about solar irradiance, air temperature and wind velocity have been supplied by plant managers and derive from both measured data and suitable data base. They have been used to calculate the hourly amount of energy supplied by the PV plant. The calculation model considers the dependence of the conversion efficiency from the PV module temperature. In this paper a tilt angle of 15° has been considered.

The engine is powered by diesel fossil fuel stored in a tank nearby and the efficiencies are function of the load. At nominal load the electrical efficiency is set equal to 0.32, while the thermal efficiency is set equal to 0.47. The minimum working load is 20% of the nominal power. The characteristics curves for the internal combustion engine are showed on Fig. 3.

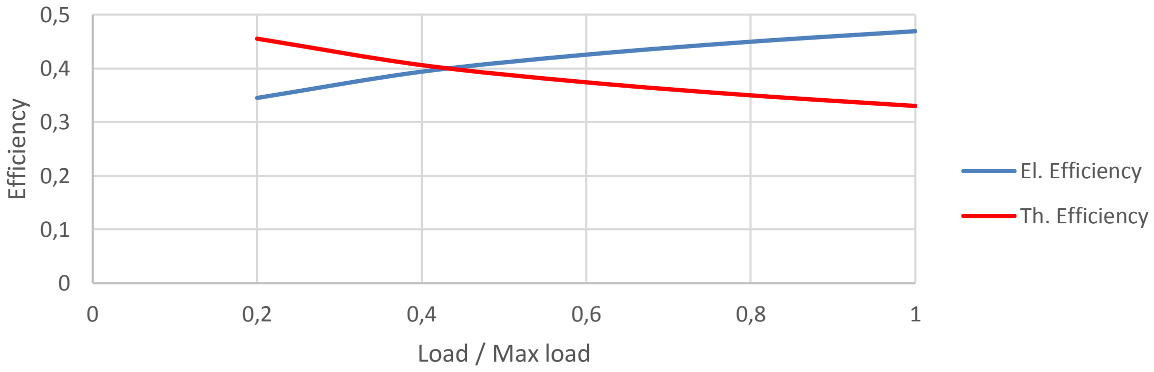


Fig. 3. Electrical efficiency curve (light blue) and thermal efficiency curve (red) for the internal combustion engine.

The boiler is powered by diesel fossil fuel stored in a tank nearby and the thermal efficiency is function of the load. At nominal load it is equal to 0.8. The minimum working load is equal to 20% of the nominal power. The efficiency curve of the boiler is showed on Fig. 4

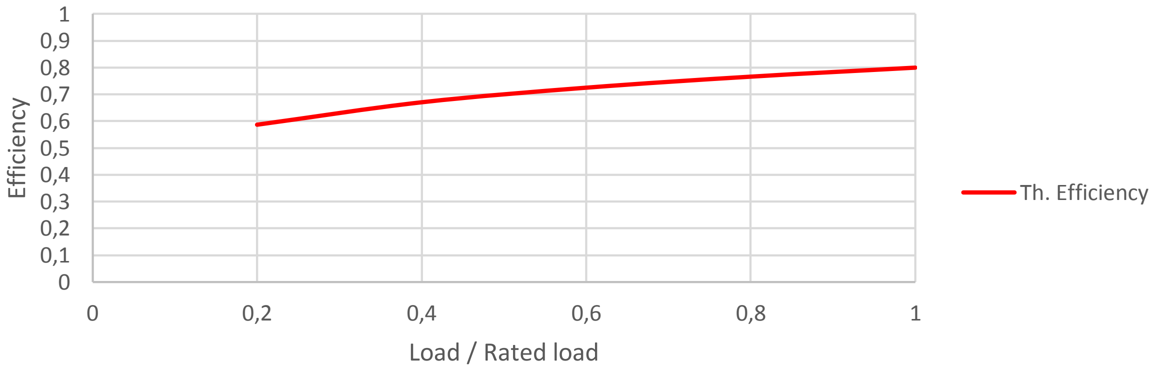


Fig. 4. Thermal efficiency curve for the boiler.

For the reversible air to water heat pump the data about the temperature of the location have been supplied to the model. A high value of load factor of the machine could help to maintain a high annual efficiency during the winter period and also during the summer period. For this reason the efficiency coefficients are fixed during each season and they don’t change with the load. The coefficient of performance (COP) during the heating operation mode is set equal to 4.07, while the energy efficiency ratio during the cooling mode is set equal to 3.70.

The efficiency of the PAT has been calculated as a function of load for both operation modes. The range of the volumetric flow rate is from 20% to 100% of the maximum flow rate during pumping operation mode and from 50% to 100% in the turbine operation condition. The maximum efficiency in both operation modes mode is set equal to 0.8. The efficiency curve of the PAT is showed on Fig. 5.

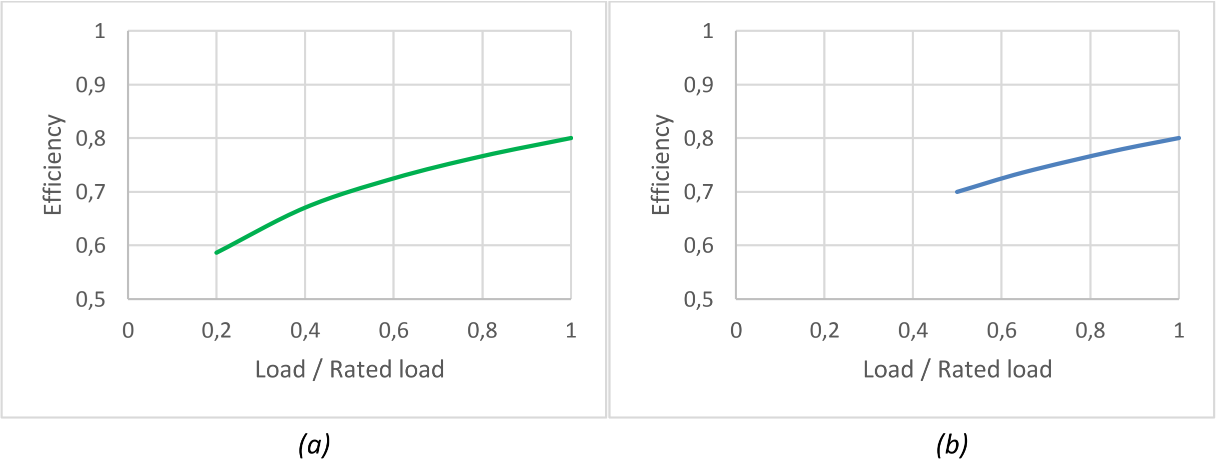


Fig. 5. Electric efficiency of the PAT: a) in pump mode, b) in turbine mode.

Water is pumped from 50 meters deep and a concrete tank has been considered for water storage. The head losses in the pumping system have been estimated as a function of the flow rate and the pipes length. The level of the water reservoir in the upper reservoir is imposed to be restored at the end of each day to the level of the morning.

The hot storage and cold storage are supposed adiabatic. The energy level of the thermal storages is imposed to be restored at the end of each day to the level of the morning.

The battery is modelled taking into account the main electrical characteristics of the acid lead battery. The round trip efficiency is equal to 0.75, the maximum charge and discharge rate is set equal to C/20 where C indicates the capacity of the battery. The lifetime of the battery depends on the number of cycles and to the deep of discharge following the graph in Fig. 6. Also for the electro-chemical storage is imposed the restore of the charge level at the end of every day.

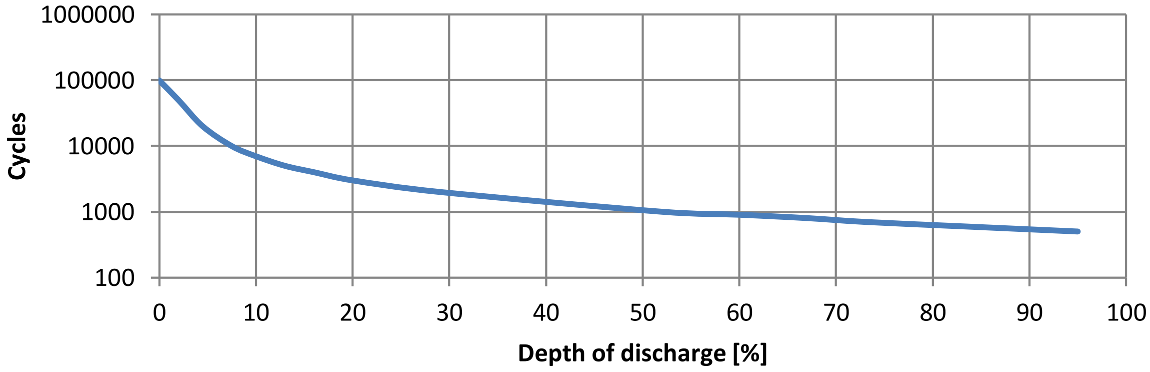


Fig. 6. Number of life time cycles of a Pb battery as a function of the depth of discharge (DoD).

2.2 - Balances relations

For each hour, the user requests are satisfy taking into account the energy balances in the follow:

Electric power balance

$P_{users}=(P_{PV}+P_{BAT})*\eta_{INV}+P_{CHP}+P_{PAT}$ if $(P_{PV}+P_{BAT})>0$ (1)

otherwise

$P_{users}=(P_{PV}+P_{BAT})/\eta_{INV}+P_{CHP}+P_{PAT}$ (2)

Heat power balance

$Q_{users}=Q_{CHP}+Q_{B}+Q_{HP}+Q_{h,storage}$ (3)

Cold power balance

$Q_{c,users}=Q_{c,HC}+Q_{c,storage}$ (4)

where P_{users} is the electric load demand, P_{PV} is the power generated by the PV, P_{BAT} the power of the battery, P_{CHP} is the power generation by the internal combustion engine, P_{PAT} is the power of the PAT. Similarly, Q_{users} is the heat demand, Q_{CHP} is the heat recovered by the internal combustion engine, Q_{B} is the heat generated by the boiler, Q_{HP} the heat generated by the reversible heat pump and $Q_{storage}$ the variation of the stored heat: it is positive, if discharging, or negative, if charging. Similarly, $Q_{c,users}$ is the cold demand, $Q_{c,HP}$ is the cold generated by the reversible heat pump and $Q_{c,storage}$ the variation of the stored cold: it is positive, if discharging, or negative, if charging.

Other constraint was the water flow rates balance:

$m_{tank}=m_{users}+m_{PAT}$ (5)

where m_{tank} is the flow rate of the tank (positive values indicate an outgoing flow rate), m_{users} is the water demand of the resort and m_{PAT} is the flow rate of the pump.

The maximum and minimum flow rate of the PAT, the maximum and minimum State of Charge of the batteries (SOC), the maximum charge/discharge rate of the batteries, the maximum and minimum load of the CHP, HP and boiler are fixed as devices characteristics.

Finally, in order not to affect the system management of the following days, it was imposed that, at the end of the day, the water in the tank, the state of charge of the battery and of the thermal storages must be equal to those at the beginning of the day:

$V_{h=24}=V_0$ (6)

$SOC_{h=24}=SOC_0$ (7)

$Qh_{h=24}=Qh_0$ (8)

$Qc_{h=24}=Qc_0$ (9)

2.3 - System operation strategy

In order to take into account the percentage of renewable energy used in the electricity production it has been defined the annual ratio

$E_{PV} / (E_{PV}+E_{CHP})$ (10)

A high value of (10) means a great use of renewable energy, but can introduce high total costs, related to a very low exploitation over the year of some devices, mainly CHP and B which often operate at low load or with a high ON/OFF cycles. In some outcomes it was possible to reach good results with a percentage of renewable energy production between 50 and 60 %.

Likewise, the ratio

$$|E_{PAT}| / (|E_{PAT}| + |E_{BAT}|) \tag{11}$$

considers the percentage of energy managed by the pumped hydro storage. Setting a high value of (11) causes a high annual cost manly caused by the lower round trip efficiency of the pumped hydro storage system than the battery pack.

In the optimization process, the analyst can enforce the minimum value of (10) and (11).

The application of a reversible heat pump instead of a conventional boiler and separated air cooling system could provide a high load factor for this machine. This approach is linked to the constraint on the operational management of CHP and B. The operational management of the thermal machines are related to the number of switching on/off of the machine and to the maximum percentage of load variations. A good compromise for these parameters is imposing in the model a maximum number of four switching/day and a load variation of 50% between two consecutive hours.

Furthermore in the model there were implemented the commercial size of the devices, so that same optimization variables are integer or not continuous functions.

2.4 - Object function

The optimization problem is arranged as a single optimization object taking into account the devices' cost, the fuel cost and the penalties for the constraint violations.

The final equation is:

$$\mathrm{F}(\mathbf{X}_\mathrm{j}) = \min(\mathrm{f}(\mathbf{X}_\mathrm{j}) + \sum_{z=1}^{nc} \lambda_z \cdot [VIOL_z]^2) \tag{12}$$

Where $f(X_j)$ is the cost function, λ_z is the penalty multiplier, $VIOL_z$ is the amount of the violation of the constraint z.

It is possible to rewrite the cost function in the following way:

$$\mathrm{f}(\mathbf{X}_\mathrm{j}) = (c_{PV}S_{PV} + c_{BAT}S_{BAT} + c_{INV}S_{INV} + c_{CHP}S_{CHP} + c_BS_B + c_{HP}S_{HP} + c_{PAT}S_{PAT} + c_{w,res}S_{w,res} + c_{th,res}S_{th,res} + c_{c,res}S_{c,res}) + \sum_{h=1}^{24}(m_{CHP,h} + m_{B,h})\Delta t \tag{13}$$

where c are the specific costs of the different devices and S their sizes, $m_{CHP,h}$ and $m_{B,h}$ [kg/h] are, respectively, the fuel mass flow rate of CHP and boiler and Δt is the considered time interval, which was fixed equal to 1 hour. As said, c_{BAT} is evaluated taking into account the batteries life span, which is as a function of their resulting operation. It is calculated by means of the relationship reported in Fig. 6 considering the actual trend of their SOC.

The main costs considered during the optimization are summarized in Table 2.

As clear, the size and the management of every single device in the system are the optimizing variables.

As mentioned, the optimization is performed by means of a model based on the Particle Swarm Optimizer (PSO) [16-19], which is a heuristic method. As suggested by many Authors [18-19], it has been chosen as it is relatively simple to be implemented and can rapidly reach the convergence, also for problems with many optimization variables. The swarm has a specified number of particles (where "particle" denotes a bird or an insect), each one characterized by a position and a velocity. The particles, initially located at random locations, wander around in the search space with a target. If *n* is the number of variables, Fan et al. suggest as criterion to assume a number of particles equal to *2n* [18]. In the procedure proposed in this paper, *np* is variable from *2n* to *8n*. The convergence is achieved when the positions of all particles converge to the same set of values. Anyway a maximum number of iterations is super imposed (in this paper, 10000 iterations).

Table 2. Specific costs of all the devices and of the fuel used in this analysis

PV	340 €/m^2
CHP	1000 €/kWel
BAT	210 €/kWh
INV	500 €/kW
PAT	220 €/kW
Cooling System	200 €/kWco
Reversible Heat Pump	300 €/kWth
Water reservoir	100 €/m^3
Boiler	51 €/kW
Hot storage	38 €/kW
Cold storage	20 €/kW
Fuel	1.4 €/l

3. Results and discussion

It is interesting to analyse the system evolution from the case 0 to the case 1 where Case 0 is referred to a system without the heat pump and with a traditional cooling system, as described in [15], while case 1 is the present model result. The resulting sizes of the main components are summarized in Table 3 as well as the annual costs.

Table 3. Main results of the simulation.

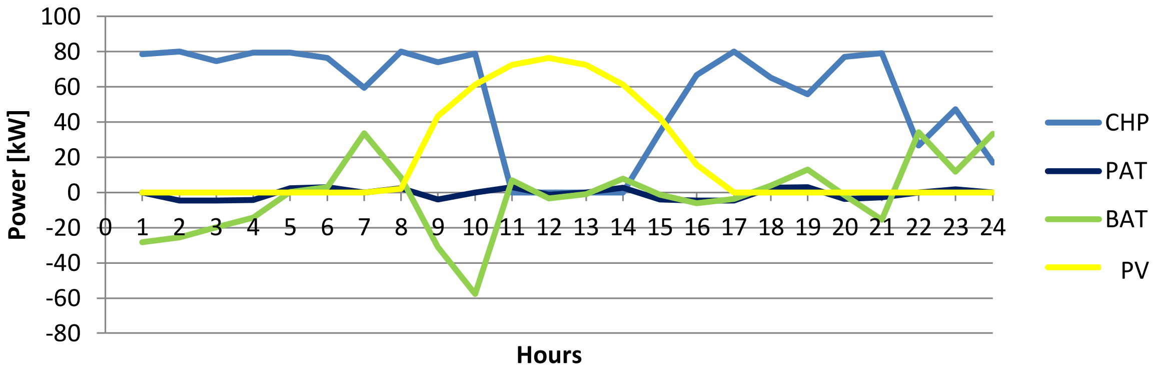
case	*PV*	*INV*	*CHP*	*REVERSIBLE HEAT PUMP*		*COOLING SYSTEM*	*BAT*	*PAT p*	*B*	*S_W*	*S_TH*	*S_CO*	*COST*
	m^2	*kW*	*kWel*	*kW th*	*kW co*	*kW co*	*kWh*	*kW*	*kW*	*m^3*	*kWh*	*kWh*	*€/y*
0	200	25	102	0	0	300	147	6.8	350	175	850	0	310000
1	600	80	80	161	146	0	400	4.6	70	88	500	1200	190000

Better outcomes are provided by the case 1 where a reversible heat pump was modelled and it was set a high number of operating hours. From the case 0 to the case 1 it is possible to recognise an increase of the PV size and a reduction of the cogenerator size linked to the boiler size reduction. The thermal storage volume is slight reduced from the case 0 because the machines sizes can avoid its use. The battery size is slight reduced from the case 0 because there is a quite constant internal energy request for the heat/cooling production.

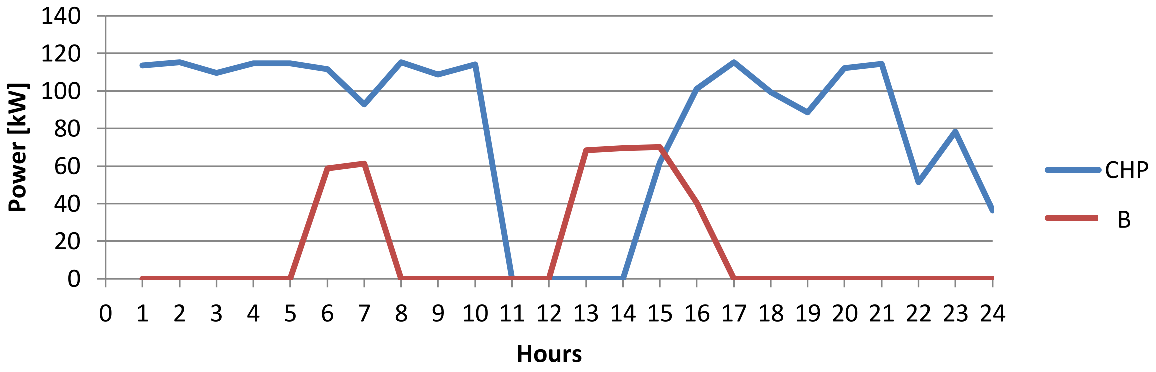
Table 4. Annual energy production.

	ENERGY			
CASE	*SOLAR*	*FUEL_CHP*	*FUEL_B*	*FUEL*
	MWh	*MWh*	*MWh*	*MWh*
0	486	4975000	4173000	9148000
1	1466	4719000	308000	5027000

Taking into account the energy that feeds the system it is possible to see a reduction of the fuel consumption. It is interesting to analyse the case 1, with a deep detail on the components' management and comparing the summer day and the winter day as reported in Fig.7 and 8.



(a)



(b)

Fig. 7. Power productions in a winter day: a) electricity, b) heat.

During the day there is a continuous modulation of the load of the machines is order to satisfy the load and observe the balances.

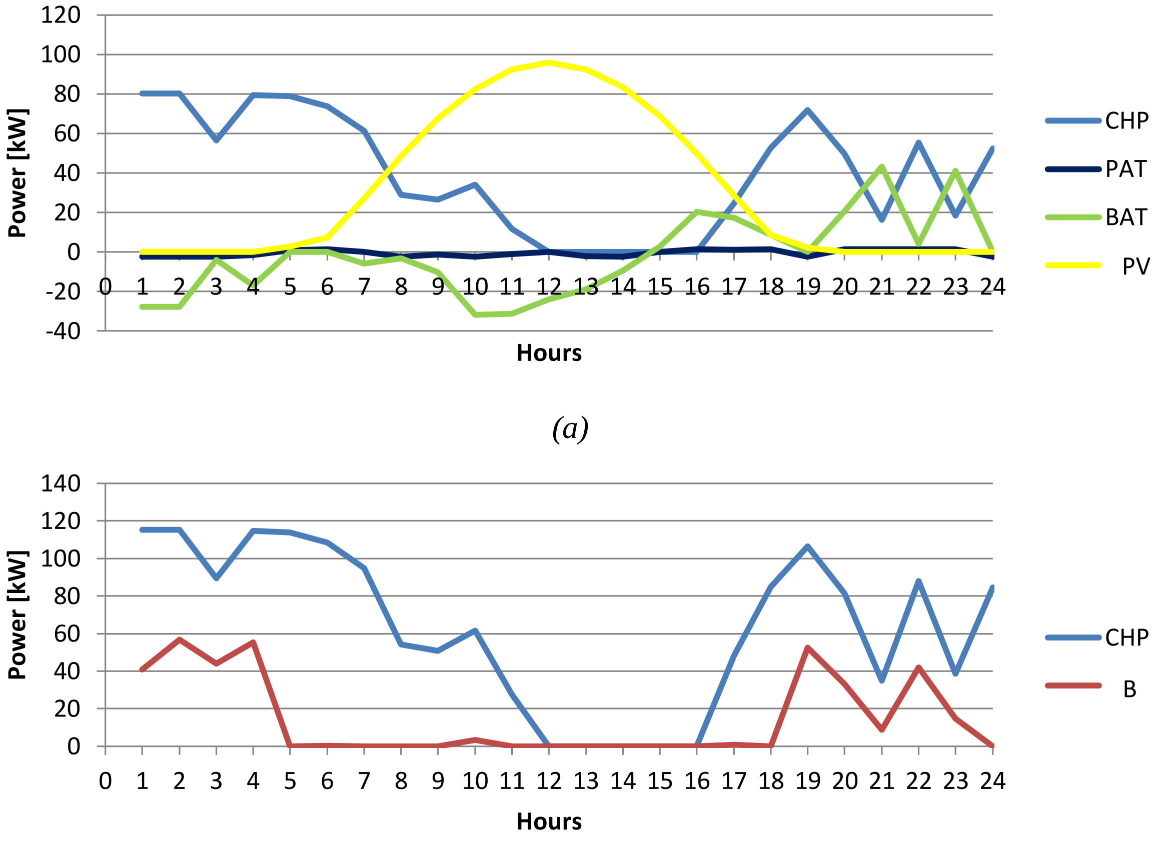
The profiles show the highest PV production in the middle hours of the day. The consequence is that the CHP engine is turned off. The battery charges during the high PV production and in the first hours of the day. The size of the battery is quite large and it is optimized by the model. For the battery model, the size of the battery influences the battery life so the model usually applies quite large sizes. The boiler works mainly to satisfy the high request and to restore the thermal storage.

About the total amount of electricity production (633000 kWh/year) the PV plant produces 35% of the total amount, while the diesel engine produces the 65%.

About the total amount of heat production (1470000 kWh/year) the reversible heat pump produces 48% of thermal request, the CHP engine produces 43%, the boiler produces 5% and the remaining part of the total heat produced is dissipated.

About the total amount of cool request, it is completely produced by the reversible heat pump.

In Fig. 8 the trends of the stored quantities are reported. It is possible to recognise the evolution in terms of stored energy for water and electricity during the sunny hours in the summer days while the CHP engine is turned off and the thermal storage is discharged.



(a)

(b)

Fig. 8. Power productions in a summer day: a) electricity, b) heat.

These results are obtained applying a variable efficiency for the machines. Also a model with constant efficiencies was run. The results from the variable efficiency model are more accurate in terms of proximity to the reality. The application of a constant efficiency, better if equal to the seasonal efficiency, provides results slight different. The main differences are in terms of cost and in terms of size of the component (within the 5%) while the sizes of the devices and the management are almost the same of those obtained with the most complex model.

With regard to the optimization method, each optimization has been performed 10 times. For all cases, more than half the solutions have a value of the cost function which differs from the optimum one for less than 5%. So the PSO solver is a good algorithm able to identify the minimum region.

Conclusions

A PSO approach to the optimization of a hybrid system has been presented and applied to the study of the energy and water needs of a small isolated touristic resort in Northern Italy. Four different services are managed: electricity, heat, cooling and water.

The optimization procedure was aimed at minimizing the overall costs. The size of all the system devices and the hourly-based profiles of their operation were simultaneously optimized considering two typical operation days.

Taking into account the ability of the solver to identify the minimum region, it will be interest to introduce some more constraint in the model to test this ability. Other stochastic methods, as Differential Evolution, for the size and management optimization are also under investigation.

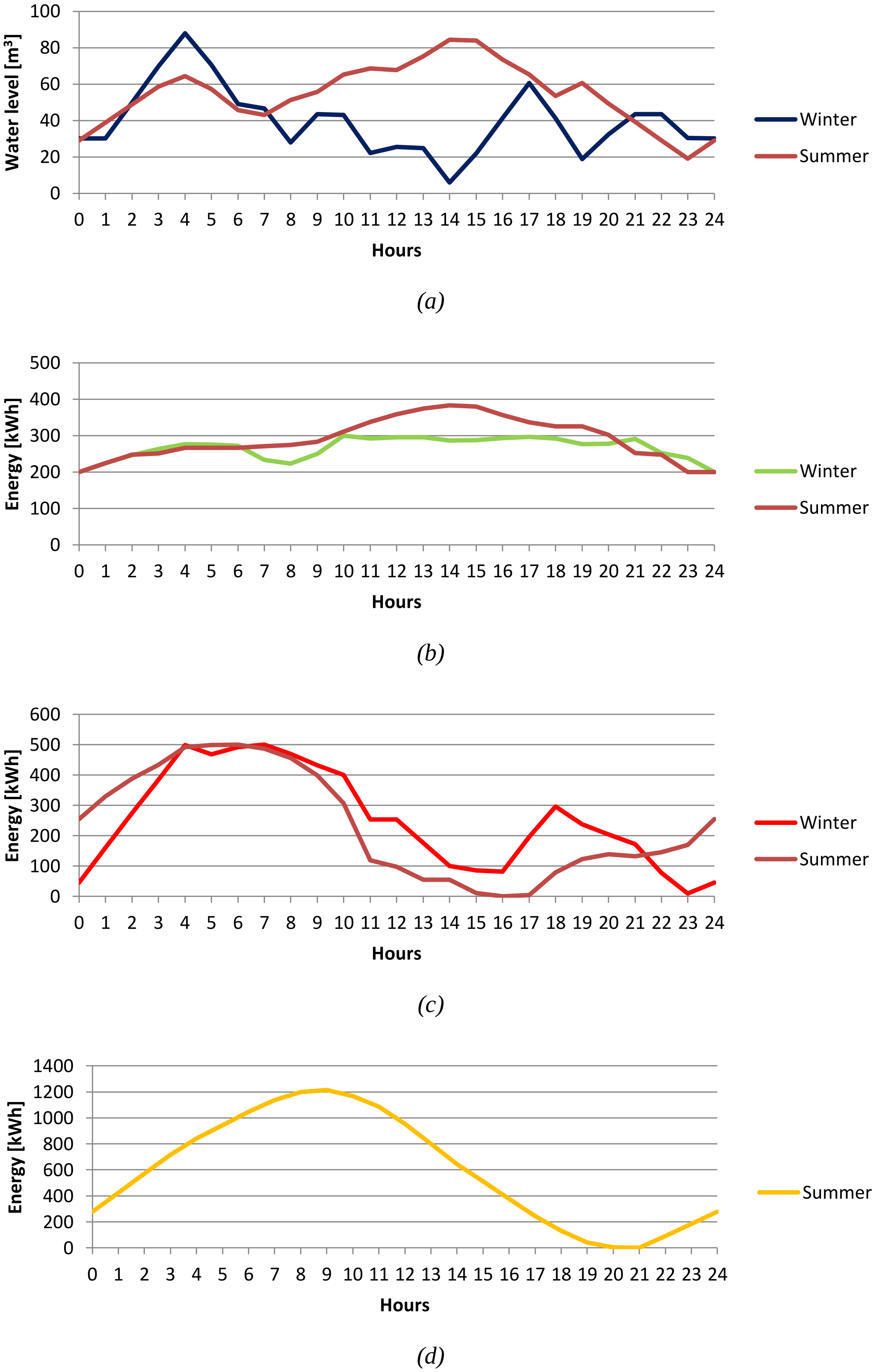


Fig. 9. Storages' trends in typical winter and summer days: a) water, b) battery, c) heat water, d) cold water.

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