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High Temperature Heat Pump with Combined Cooling, Heat and Power Plant in Industrial Buildings: An Energy Analysis

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ABSTRACT

In this paper, the coupling of a high temperature heat pump with a combined cooling, heat, and power system is investigated. The plant converts the input energy source (natural gas) into electricity and useful thermal energy by means of a cogenerator. Part of the thermal energy feeds an absorption chiller that produces the cooling energy to satisfy the cooling load of an existing industrial building located in northern Italy. The heat pump enhances the low temperature heat from the condenser and absorber of the absorption chiller to high temperature heat to integrate the hot water produced by the cogenerator. The energy performance of the entire plant is analyzed by means of steady-state simulations at both fixed conditions and on an annual operation to meet the heating, cooling, and electric needs of the building varying different parameters and compared to traditional systems for energy production. As the main results, the integrated system provides flexibility and achieves valuable energy performances, in the range of a few tens of percent with respect to benchmark energy production systems.

1. INTRODUCTION

In this study, the revalorization of low temperature heat in a trigeneration or combined cooling, heating, and power (CCHP) plant in an industrial application is analyzed, studying the performance from both an energy and exergy point of view.

The system proposed here, with a CCHP coupled to a High Temperature Heat Pump (HTHP), is a “total energy” system. These are polygeneration energy systems that feature both the heat reservoirs (source and sink) at temperatures different from ambient temperature [1, 2]. They can be an energy-efficient, environmentally friendly, and cost-effective alternative to separate production [3].

Many authors recently studied different polygeneration systems. For example, Cannistraro et al. [4] evaluated the technical and economic feasibility of the integration of a cogeneration and trigeneration system fueled with natural gas in an existing dairy industry, located in the north of Italy. Hai et al. [5] presented a study in which the waste heat of a geothermal-driven double flash cycle was efficiently recovered by a Kalina cycle and a thermoelectric generator. The further production of cooling energy and electricity by the heat recovered by the Kalina cycle and the hydrogen production by the output power of the high pressure turbine of the double-flash cycle allow an exergy efficiency of the system of 35.6%. An analysis of a renewable polygeneration system was presented that integrates solar, geothermal, and biomass energies, with the optimization of the control strategy of the energy flows between power systems, storage facilities, and utilities [6]. In study [7], different plant layouts and their part load operation were analyzed for geothermal heat source temperatures between 110 and 150°C, revealing a maximum exergy efficiency of 34.1%. Furthermore, the effect of energy subsidies on polygeneration systems was analyzed, revealing that they are significantly co-integrated with innovation in energy technology [8]. The authors stated that their removal stimulates technological innovation, which induces the adoption of a renewable-based polygeneration system.

In the past, many papers have focused on the integration of different energy technologies in polygeneration systems. In study [9], a model and an optimization procedure for hybrid wind-hydrogen combine heat and power (CHP) systems were developed. Instead, a ground source heat pump was integrated with an organic Rankine cycle in a trigeneration system by Kang et al. [10]. District heating networks supplied by cogeneration plants and their integration with heat pumps were investigated in study [11]. Leiva-Illanes et al. [12] proposed the analysis of a solar polygeneration plant for the combined production of electricity, water, cooling and heating from the energy and economic point of view.

The author of the present paper has already studied total energy systems in the past, and in particular cogeneration systems. In study [13], a comparison from the energy, economic, and environmental point of view between the gas engine heat pump integrated with the condensing boilers plant of one of the Department buildings with traditional systems was presented, revealing its high performance. In study [14], the cost of heat and power produced by the main district heating technologies based on natural gas was compared to the cost of producing the same quantity of electrical energy by a reference gas turbine combined cycle (actually the most efficient technology for pure electrical production) and the cost of production of heat by modern local heating technologies using natural gas as fuel (condensing boilers, electrical, gas engines and absorption heat pumps). More recently, the author focused on how cluster analysis can be applied to analyze energy consumption data to design cogeneration systems in a more efficient way [15, 16].

As is well known, trigeneration systems are set up by a prime mover (e.g., an internal combustion engine) that converts the non-renewable primary energy of the input fuel, typically natural gas (NG), into electric power, useful heating energy, and useful cooling energy by means of thermally driven cooling technology [17, 18]. The absorption chiller is the most widely diffused technology for the generation of cooling from recovered heat [19, 20]. As the typical energy efficiency ratio (*EER*) of the absorption chiller is low (0.7-0.9 depending on the number of effects of the chiller), a high amount of heat from the condenser/absorber is dissipated to the heat sink (usually the external air) by means of cooling towers or air coolers. This thermal energy at low temperature (30-40°C) could be usefully used by increasing its thermal level by means of a high temperature heat pump. This is a heat pump with a heat sink temperature between 85°C and 160°C [21], using low or medium temperature heat as a heat source. Interest in such technology has increased over the last years [22-25], mainly in industrial uses to provide medium or high temperature heating [26, 27]. This is generally supplied by inefficient auxiliary systems (e.g., boilers and electric heaters).

As the main purpose and novelty of this study, a further development of a previous work [28] is presented. In such a study, the integration of a high temperature vapor compression heat pump in the CCHP system (CCHP+HTHP) was investigated to cover the electric, heating, and cooling needs of an industrial user. The low temperature heat available from the condenser/absorber of the absorption chiller was recovered and used as the heat source of an HTHP to increase its thermal level for heating applications. In study [28], the authors analyzed the system (an internal combustion engine that produced both electricity and heating, a single effect absorption chiller and a HTHP) from both the exergy and economic point of view, providing an optimization sizing of the main equipment for a specific case study.

In the present study, the further novelty and main scopes are:

- analyzing the performance of the proposed system both from the energy and exergy point of view, comparing to benchmark systems for energy production (i.e., separate production, cogeneration, and conventional trigeneration) at fixed values;
- evaluating the energy and exergy viability of the proposed CCHP+HTHP system varying some input parameters, such as the type of prime mover, the coefficient of performance of the HTHP (COP_{HTHP}), and the global electrical efficiency for the electricity from the grid ($\eta_{el,ref}$);
- investigating the annual performance in steady-state operation based on energy demand data for an industrial user (a factory of a pharmaceutical company located in Tuscany (Italy) based on study [28]).

The structure of the paper is set up by the Methods section, where the models of the CCHP+HTHP and the benchmark plants are described, and the Results and Discussion section, where the simulation results are reported first at fixed values and then in annual operation for the industrial case study. Finally, some remarks on the annual energy comparison and future developments are reported in the Conclusions.

2. METHODS

2.1 Description of the CCHP+HTHP system

The CCHP+HTHP system is set up by:

- the prime mover that can be an internal combustion engine (ICE), a gas turbine (GT), a phosphoric acid fuel cells generator (PAFC) or a molten carbonate fuel cells generator (MCFC). It converts the primary energy of natural gas in input (F_{cog}) to electricity (E_{cog}) that can be directed to cover the user's electricity demand (E_{user}) and, by means of a suitable heat recovery system, to useful heat (Q_{cog}). The latter can be used in part (f) to feed the absorption chiller for cooling purposes ($Q_{abs,gen}$) and in part direct to the user ($(1-f)\cdot Q_{cog}$). A small part of energy is wasted as non-useful heat, Q_{wasted};
- the absorption chiller (abs) whose generator is fed by a variable (proportional to f) quota of Q_{cog} and produces cooling power in the evaporator ($Q_{abs,ev}$);
- the high temperature heat pump (HTHP) uses the low-temperature heat available from the condenser/absorber of the absorption chiller ($Q_{abs,cond}$) as a heat source in the evaporator to produce hot water at 90°C at the condenser ($Q_{HTHP,cond}$). This thermal energy contributes to cover the user heating demand (Q_{user}).

A schematic of the proposed system is shown in Figure 1, where the main energy flows are reported. Auxiliary units may be necessary such as an auxiliary boiler and an auxiliary electric chiller for covering the heating ($Q_{boiler\_to\_user}$) and cooling ($Q_{chil,ev}$) demand, respectively.

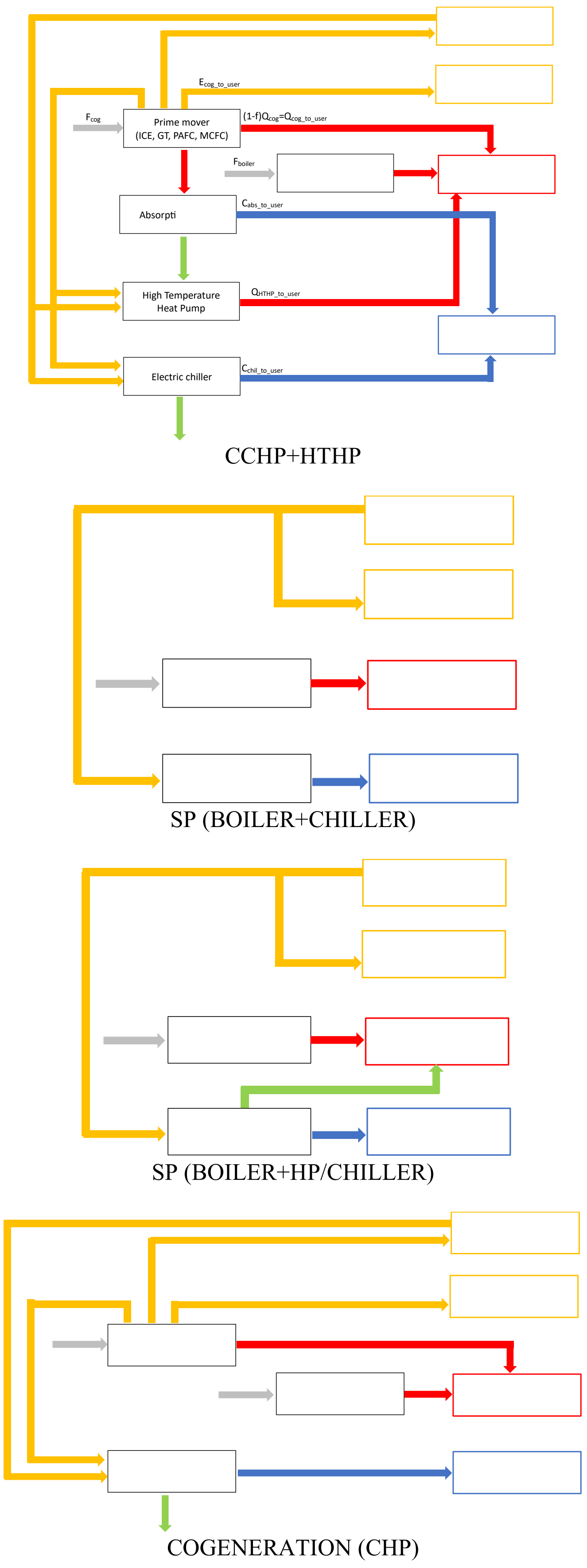
Once the nominal (electric) power of the prime mover is set, then the nominal heat recovered is known. Consequently, the nominal cooling capacity of the absorption chiller can be defined to use all the recovered heat. Then the nominal capacity of the HTHP is chosen to exploit all the low temperature heat available from the absorption chiller.

The meaning of parameter f is to provide flexibility in the operation of the system: it defines how much of the heat recovered from the prime mover (Q_{cog}) feeds the absorption chiller ($Q_{abs,gen}=f\cdot Q_{cog}$) and, consequently, the quota directly used to satisfy the heating demand. Limit cases are when f=0 (no heat from the prime mover is used to feed the absorption chiller, so there is no cooling production) and f=1 (the cooling production is maximized as all heat recovered from the prime mover feeds the absorption chiller, and the heating demand is covered only by the HTHP).

The electric, heating and cooling production of the system as a function of f is depicted in Figure 2 in normalized terms (fuel input F_{cog} equal to 1 MW) with given values of the efficiencies of the main equipment. Four cases are reported varying the electric efficiency of the cogenerator and the *COP* of the HTHP for two typical values (0.35 and 0.45, 3 and 4, respectively) to consider the availability of different technologies. $\eta_{el,cog}$=0.35 is typical for a GT or PAFC, while 0.45 is typical for an ICE or MCFC [29]. COP_{HTHP}=3 is a typical value for newer refrigerant (e.g., R1234ze(E)) while 4 is a typical value for ammonia [30]. From Figure 2 it is apparent that electricity production may also be negative, which means that the energy system does not produce electricity, instead it needs electricity from the grid to feed the HTHP. The limit value of f for which the electricity production becomes negative is (Eq. (1), Eq. (2)):

$$E_{cog_{touser}} = \eta_{el,cog}F - (1 + EER_{abs})f\eta_{th,cog} \cdot \left(\frac{1}{COP_{HTHP} - 1}\right)F = 0 \tag{1}$$

$$f = \frac{\eta_{el,cog} \cdot (COP_{HTHP} - 1)}{(1 + EER_{abs})\eta_{th,cog}} \tag{2}$$



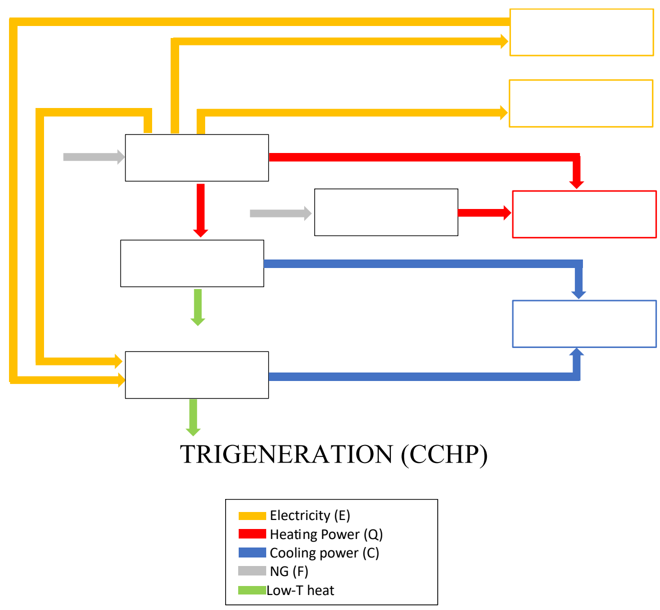


Figure 1. Schematic of the CCHP+HTHP integrated system and the benchmark systems considered in this study

The thermodynamic performance of the proposed trigeneration system (Figure 2) and all benchmark systems described in Section 2.2 (and shown in Figure 1) are evaluated in terms of the following indexes:

- primary energy ratio of the whole system (PER_{tot}), defined as the ratio between the sum of the useful energy and the sum of the total non-renewable primary energy consumed by the plant (Eq. (3));
- exergy efficiency of the whole system ($\eta_{ex,tot}$), calculated as the ratio between the exergy flow of the products and the exergy flow in input (Eq. (4) where reference temperature T_0=20°C, useful thermal energy temperature T_Q=90°C, useful cooling energy temperature T_C=10°C).

In order to equitably compare different system configurations, the primary energy (and exergy) input to which the analysis refers is always the fuel chemical energy (which is equal to its exergy). For this reason, the electricity bought from the grid has an exergy efficiency equal to the global thermoelectric efficiency $\eta_{el,ref}$, that is, the global efficiency of the electricity from the grid produced by a thermoelectric plant fueled by fossil fuels (non-renewable primary energy). Such a parameter will be considered variable in the following analysis to compare different scenarios:

- $\eta_{el,ref}$=0.4: refers to the "recent past" situation in Italy (say, the first 2000);
- $\eta_{el,ref}$=0.5: refers to the actual situation in Italy [31];

As depicted in Figure 2, the variation of $\eta_{el,cog}$ and COP_{HTHP} does not influence the cooling power (C) produced by the system; instead, they determine the electrical and thermal power: for a given value of f, increasing $\eta_{el,cog}$ increases E with Q quite constant, while increasing COP_{HTHP} reduces Q produced by the system. It should also be noted that the exergy efficiency of the proposed system strongly increases with the increase of the COP of the HTHP and the electrical efficiency of the prime mover.

$$PER_{tot} = \frac{\left(Q_{cog_{touser}} + Q_{HTHP_{touser}} + Q_{boiler_{touser}}\right) + \left(C_{abs\_to\_user} + C_{chil\_to\_user}\right) + \left(E_{cog\_to\_user} + E_{from\_grid\_to\_user}\right)}{F_{cog} + \frac{Q_{boiler_{touser}}}{\eta_{boiler}} + \frac{E_{from\_grid\_to\_user} + E_{from\_grid\_to\_HTHP} + E_{from\_grid\_to\_chil} - E_{cog\_to\_grid}}{\eta_{el,ref}}} \quad (3)$$

$$\eta_{ex,tot} = \frac{\left(Q_{cog_{touser}} + Q_{HTHP_{touser}} + Q_{boiler_{touser}}\right)\cdot\left(1-\frac{T_0}{T_Q}\right) + \left(C_{abs\_to\_user} + C_{chil\_to\_user}\right)\cdot\left(1-\frac{T_0}{T_C}\right) + \left(E_{cog\_to\_user} + E_{from\_grid\_to\_user}\right)}{F_{cog} + \frac{Q_{boiler_{touser}}}{\eta_{boiler}} + \frac{E_{from\_grid\_to\_user} + E_{from\_grid\_to\_HTHP} + E_{from\_grid\_to\_chil} - E_{cog\_to\_grid}}{\eta_{el,ref}}} \quad (4)$$

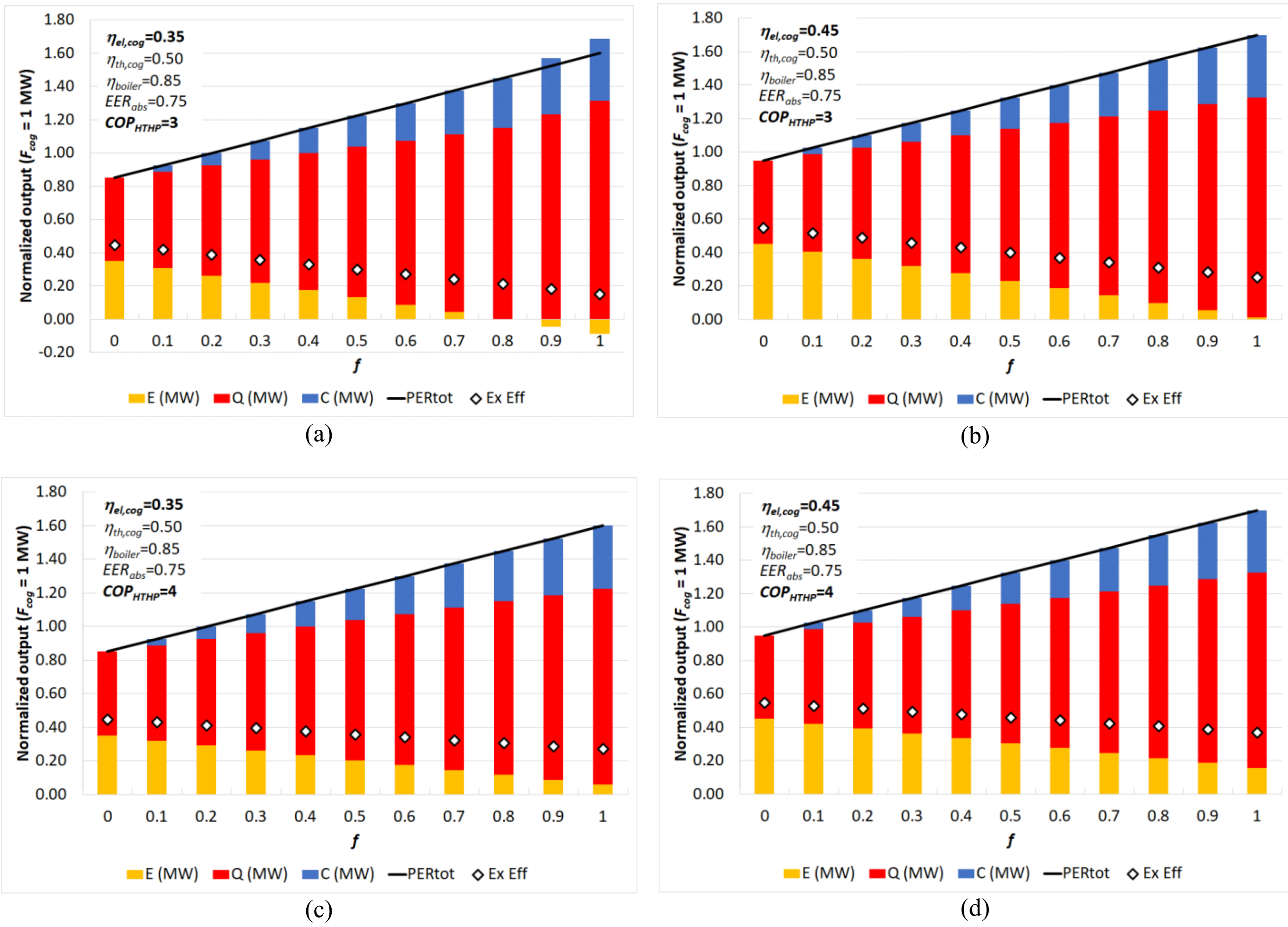


Figure 2. Power output, energy and exergy performance of the CCHP+HTHP system varying the fraction of cogeneration recovery heat to cooling (f) for 1 MW of NG input ($\eta_{el,ref}$=0.5)

In the following analysis, an E_{user}-following operation mode of the CCHP+HTHP system was considered, i.e., the cogenerator is operated to cover the electricity demand from the user (E_{user}) in all the time step of the simulation, with the electricity from the grid ($E_{from\_grid\_to\_user}$) covering the possible deficit. In this case, the heat from the cogenerator facing the heating demand ($Q_{cog\_to\_user}$=(1-f)·Q_{cog}) and the absorption chiller ($Q_{abs,gen}$=f·Q_{cog}) can be not enough, and an integration boiler and electric chiller may be necessary, respectively.

The Q_{user}-following operation mode was not considered to be interesting: in this case, the cogenerator would be operated to cover the heating demand from the user (Q_{user}) in all the time steps of the simulation, with the thermal energy produced by the HTHP ($Q_{HTHP\_to\_user}$) and the integration boiler ($Q_{boiler\_to\_user}$) covering the possible deficit. In this case, no thermal energy would be available to feed the absorption chiller, thus no trigeneration would be realized.

2.2 Description of the benchmark systems

The energy performance of the combined trigeneration high temperature heat pump plant was compared to other benchmark systems for energy production to evaluate the conditions in which the proposed system performed better than traditional ones:

- separate production system with boiler (η_{boiler}=0.85) + electric water/water chiller (EER_{chil}=3 supposed to be constant) (SP Boiler+Chiller);
- separate production system with boiler (η_{boiler}=0.85) + electric water/water chiller (EER_{chil}=3 supposed to be constant) with recovering of the heat of condensation of the chiller to pre-heat the hot water, so decreasing the energy produced by the boiler;
- cogeneration (CHP): The same prime mover of the CCHP+HTHP system was supposed to be operated, with an electric water/water chiller (EER_{chil}=3

supposed to be constant) to cover the cooling load (C_{user}) and an integration boiler (η_{boiler}=0.85) to integrate the heating load (Q_{user});

- trigeneration system (CCHP): the same as the CCHP+HTHP system without the HTHP.

The benchmark systems are depicted in Figure 1.

Table 1 reports the electrical and thermal efficiencies of the four prime movers in partial operation (values at capacity ratio = 1 are the nominal values) [32]. Note that a minimum capacity ratio of 0.3 was considered for all the prime movers.

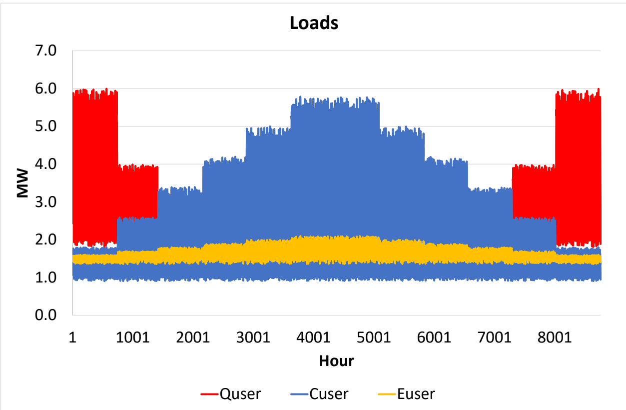


Figure 3. Electric (E_{user}), thermal (Q_{user}) and cooling (C_{user}) hourly loads for the annual simulation

In Figure 3 the electric, thermal, and cooling hourly loads for the annual simulation are reported. They approximate the data of the industrial user based on study [28]. The nominal power of the equipment for the simulation are: E_{cog}=2 MW, C_{abs}=1 MW, C_{chil}=5.2 MW, Q_{HTHP}=3.5 MW, Q_{boiler}=6 MW.

3. RESULTS AND DISCUSSION

3.1 Energy analysis at fixed values

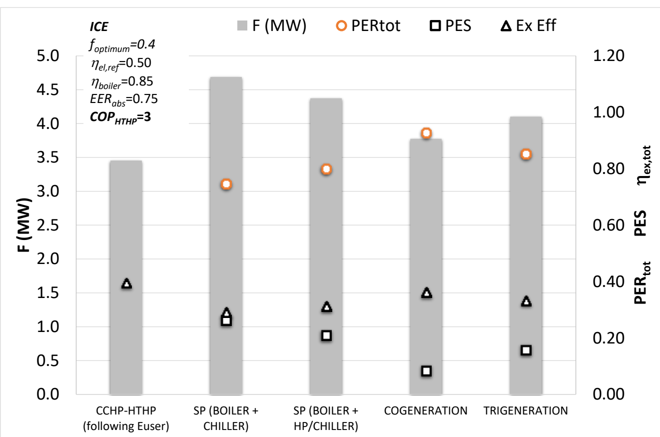
A first comparison between the described systems is reported for a single point of operation. Energy systems are compared at the same user's demands (E_{user}=1 MW, Q_{user}=2 MW, C_{user}=0.5 MW).

Figure 4 reports the non-renewable primary energy consumed by the plants, their PER_{tot} and exergy efficiency, and the primary energy saving (*PES*) of the CCHP+HTHP with respect to the benchmark systems. The results are reported for the different prime movers considering the optimal value of *f* (the one that maximizes the PER_{tot} and the $\eta_{ex,tot}$) for two different values of the COP_{HTHP} of the HTHP. The following main considerations can be found:

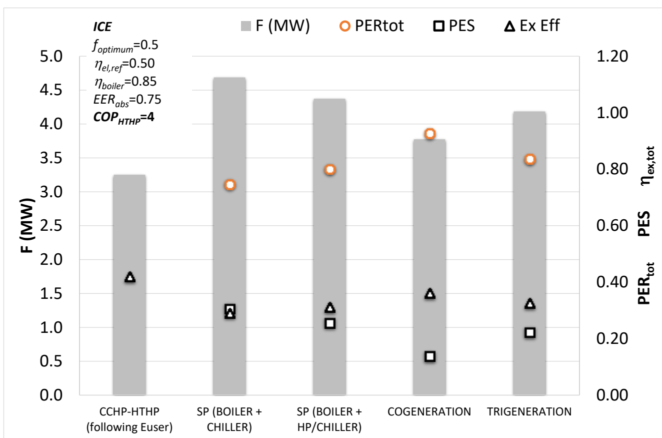
- the case with GT is not reported in Figure 4 as with this prime mover the CCHP+HTHP system is not advantageous with respect all the other benchmark systems, that is, *PES* is negative. This is due to the lower value of the electrical efficiency of GT (Table 1);
- for each configuration there is a different optimum value of *f*, that is, the quota of the thermal power produced by the prime mover feeding the absorption chiller to satisfy the cooling load has to be optimized for the particular configuration considered;

Table 1. Electric and thermal efficiency of the prime movers [32]

Capacity Ratio	$\eta_{el,cog}$				$\eta_{th,cog}$			
	ICE	GT	PAFC	MCFC	ICE	GT	PAFC	MCFC
0	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
0.1	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
0.2	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
0.3	35.18%	14.52%	33.80%	44.18%	52.82%	73.48%	54.20%	43.82%
0.4	37.77%	18.43%	34.75%	44.99%	50.23%	69.57%	53.25%	43.01%
0.5	39.77%	21.47%	35.49%	45.62%	48.23%	66.53%	52.51%	42.38%
0.6	41.41%	23.94%	36.09%	46.14%	46.59%	64.06%	51.91%	41.86%
0.7	42.80%	26.04%	36.60%	46.57%	45.20%	61.96%	51.40%	41.43%
0.8	44.00%	27.85%	37.05%	46.95%	44.00%	60.15%	50.95%	41.05%
0.9	45.06%	29.46%	37.44%	47.28%	42.94%	58.54%	50.56%	40.72%
1	46.01%	30.89%	37.79%	47.58%	42.00%	57.11%	50.21%	40.42%



(a)



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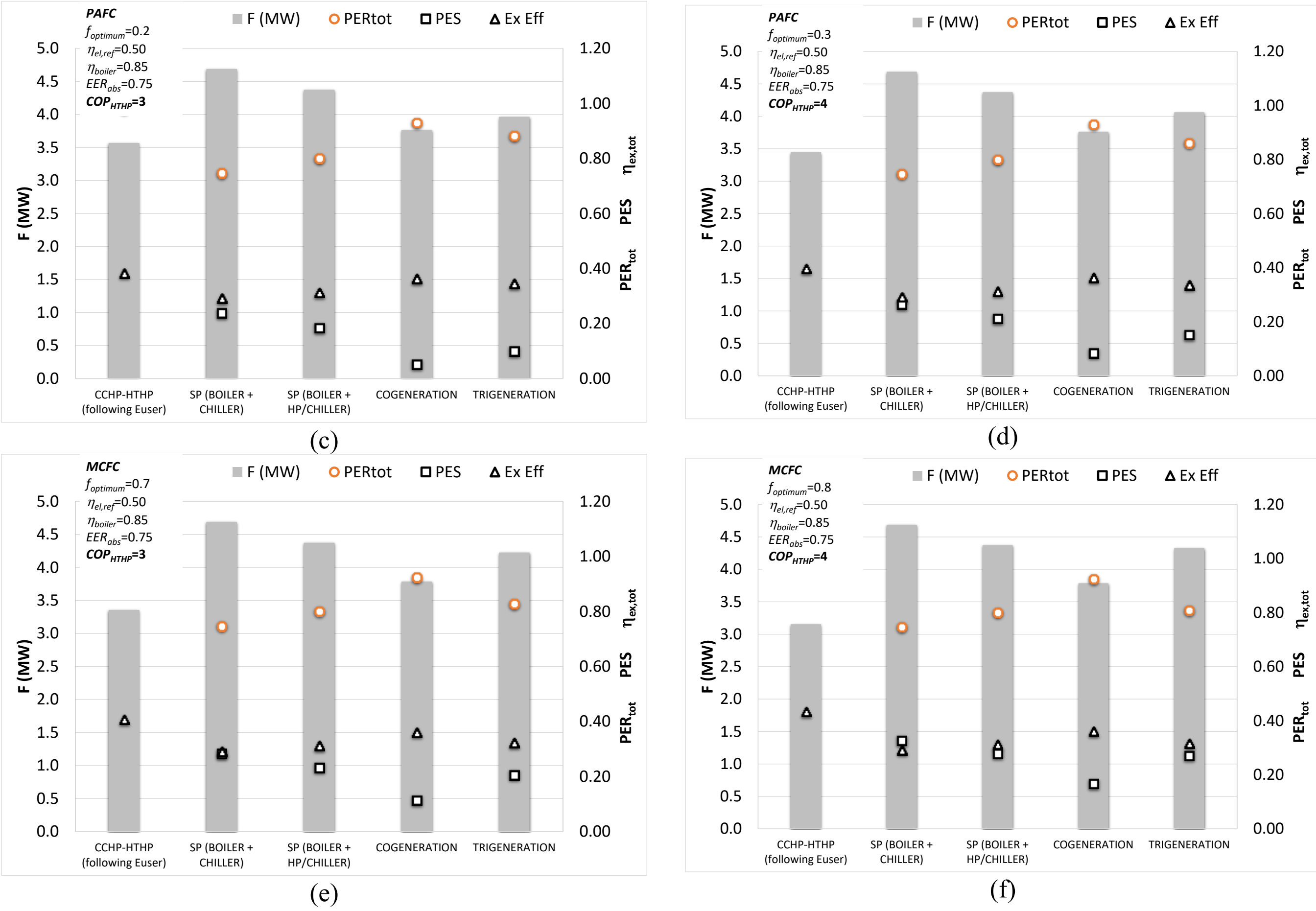

Figure 4. Non-primary energy power input (*F*), energy and exergy performance (PER_{tot} and $\eta_{ex,tot}$, respectively) of the systems, and primary energy savings (*PES*) of CCHP+HTHP with respect to the benchmark systems

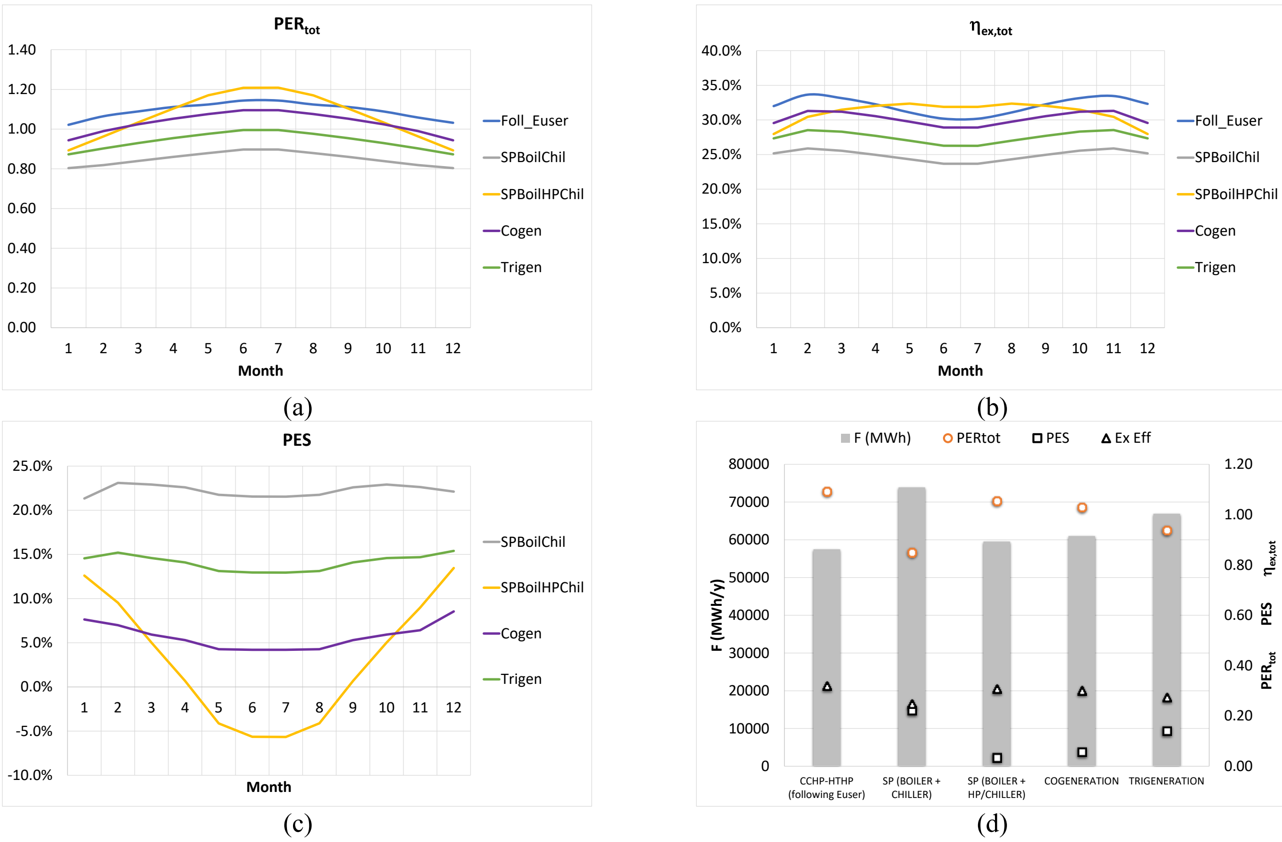

Figure 5. Monthly values of the primary energy ratio (a), exergy efficiency (b), and primary energy saving (c) of CCHP+HTHP with respect to the benchmark systems; annual values of energy performance of the systems (d) (with optimized values of *f* for each month)

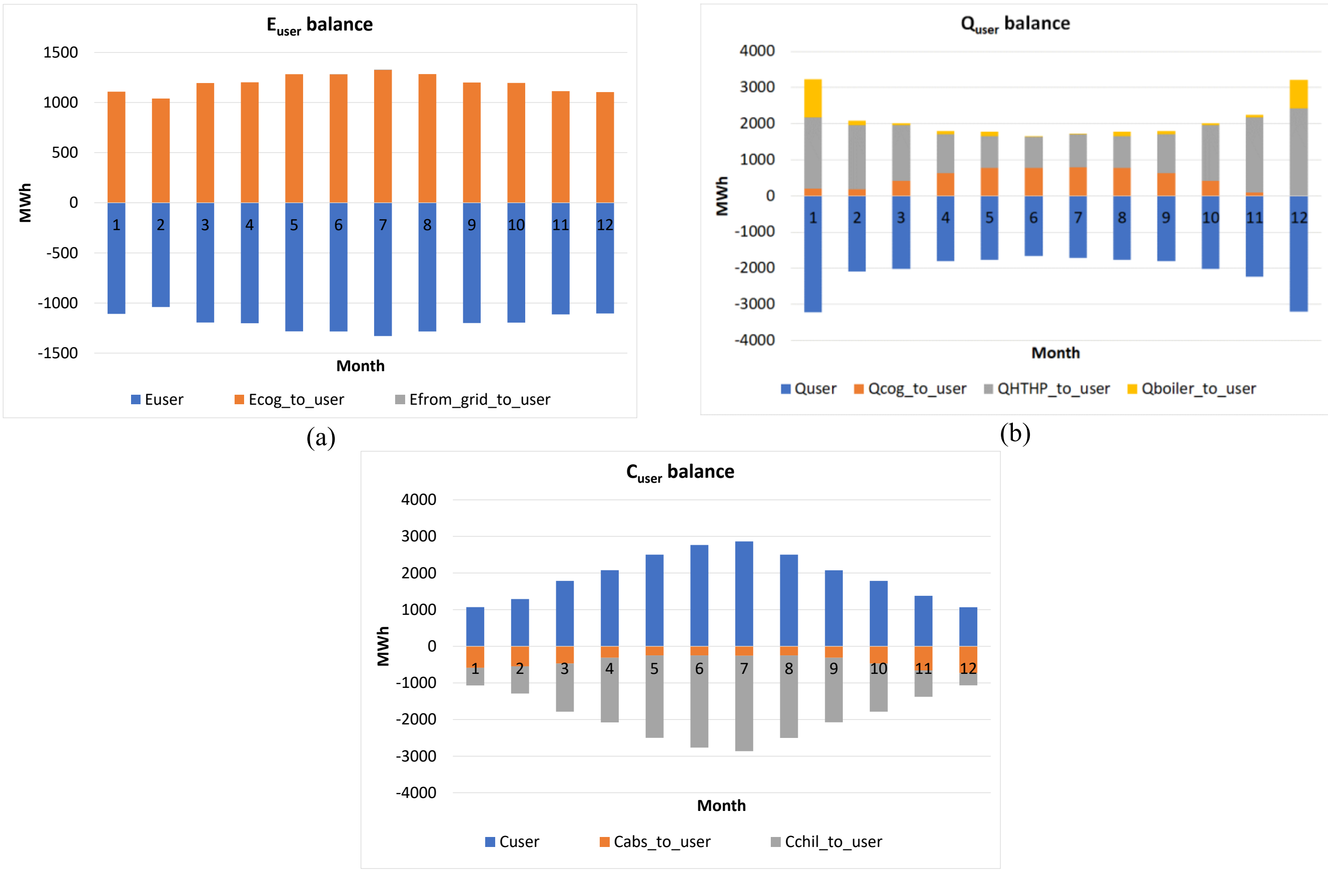

Figure 6. Monthly energy balance of the user' electricity demand (a), thermal energy demand (b) and cooling energy demand (c)

- the optimum value of f increases when considering more electric-efficient prime mover technologies (it increases from ICE to PAFC to MCFC). The more efficient is the system from the electric point of view, the more advantageous is to direct a greater quota of heat to the absorption chiller and then to the high-temperature heat pump as the latter is fed by electricity produced by the prime mover;
- the optimum value of f increases when increasing the COP_{HTHP}, as it is more advantageous to produce heating power from the HTHP instead of recovering heat from the prime mover;
- in all the configurations here considered, a positive *PES* was obtained, that is, the CCHP+HTHP can always be the most advantageous solution from the energy and exergy point of view;
- in all the configurations here considered, the greatest (positive) *PES* (i.e., the best energy and exergy performance of the CCHP+HTHP system) is respect to the separate production (SP Boiler+Chiller). Then follows the SP (Boiler+HP/Chiller), the trigeneration and the cogeneration systems.

3.2 Annual energy analysis

Figure 5 reports the energy performance of the systems both on a monthly basis (parts (a)-(b)-(c) of the figure) and on an annual basis (part (d)). Results are reported for the optimum value of f for each month. On an annual basis, the CCHP+HTHP system allows a better performance with respect to all other benchmark systems: the PER_{tot} and the $\eta_{ex,tot}$ are the highest, and the non-renewable primary energy consumption F is the lowest. In decrescent order, PER_{tot} is 1.09, 1.05, 1.03, 0.94, 0.85, and $\eta_{ex,tot}$ is 32%, 30.9%, 30.2%, 27.5%, 24.9% for CCHP+HTHP, SP (Boiler+HP/Chiller), Cogeneration, Trigeneration, SP (Boiler+Chiller), respectively. The *PES* of the CCHP+HTHP system is 3.5%, 5.8%, 14.1%, 22.2%, respectively (Figure 5d). Such results are determined by a greater efficiency of the CCHP+HTHP system in each month with respect to all benchmark systems. Only the SP (Boiler+HP/Chiller) system features a better performance of the proposed integrated system during the summer months (from May to September).

Finally, Figure 6 reports the monthly balance of the user's electricity demand (Figure 6a), the heating energy demand (Figure 6b) and the cooling energy demand (Figure 6c). The cogenerator fully satisfies electricity demand, while it covers the greatest part of heating demand (around 50%) only during summer months (when lower heat is requested to feed the absorption chiller). During the other months heating demand is covered mainly by the HTHP (only in the coldest months there is a significant contribution by the boiler, Figure 6b). The cooling demand is mainly satisfied by the electric chiller during summer months, while the main contribution is from the absorption chiller during winter months.

4. CONCLUSIONS

In this paper, a high temperature heat pump using ammonia as working fluid was integrated within a trigeneration system to produce hot water at 90°C for industrial uses.

The steady-state simulation was developed both at fixed conditions and on an annual basis. Energy and exergy analysis revealed that the CCHP+HTHP system performs better than the benchmark systems only if the prime mover has a fair good electrical efficiency as in this case it is advantageous to use the electricity produced in cogeneration to feed the HTHP. The quota of heat recovered by the cogenerator to feed the absorption chiller must be optimized to have the best energy performance of the integrated system. The main result is that the higher the electrical efficiency of the cogenerator and the *COP* of the high-temperature heat pump, the greater is the optimum value of f for the exergy performance of the system to be higher than conventional alternatives.

The integration of the proposed trigeneration system into an existing separate production plant of an industrial user was investigated. It was found that 3.5%, 5.8%, 14.1%, and 22.2% savings were provided compared to traditional separate production (Boiler+HP/Chiller), cogeneration, trigeneration, and separate production (Boiler+Chiller) systems, respectively.

Based on these first results, as a further development of this work a dynamic simulation model of the system will be developed, with the scope of optimizing the fraction of heat to feed the absorption chiller (f) for each time step of the simulation, and optimizing the size of the main equipment. An economic analysis will be useful to assess the economic viability of the proposed energy system and its profitability compared to conventional technologies.

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NOMENCLATURE

abs	absorption chiller
C	cooling power (MW), cooling energy (MWh)
CHP	combined heat and power (cogeneration)
CCHP	combined cooling, heating and power (trigeneration)
COP	coefficient of performance
E	electric power (MW), electric energy (MWh)
EER	energy efficiency ratio
F	input fuel (power, MW or energy, MWh)
f	fraction of the cogeneration heat to feed to absorption chiller
GT	gas turbine
HP	heat pump
HTHP	high temperature heat pump
MCFC	molten carbonate fuel cell
PAFC	phosphoric acid fuel cell
PER	primary energy ratio
PES	primary energy saving
Q	thermal power (MW), thermal energy (MWh)
SP	separate production
T	temperature (K)

Greek symbols

η	efficiency

Subscripts

0	reference temperature (293.15 K)
abs	absorption chiller
boiler	boiler
C	cooling temperature
chil	electric chiller
el	electric
ex	exergy
grid	electric grid
HTHP	high temperature heat pump
optimum	optimum
Q	heating temperature
ref	reference
th	thermal
user	user