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Energy retrofitting of residential buildings—How to couple Combined Heat and Power (CHP) and Heat Pump (HP) for thermal management and off-design operation

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ABSTRACT

Cogeneration (CHP) and Heat Pump (HP) are playing a key role in energy systems due to their high efficiency, especially, in energy refurbishment of buildings and industrial processes. This paper explored the opportunity to couple those two well-established technologies for heating purposes. Basically, the coupling entails limitations and constraints consisting of the mismatch between the power sizes of merchandised machines as well as the deriving technical issues. The main aim of this paper is to analyse the coupling procedure to help HVAC specialists in their job. This paper deals with a simple model formulation, based on the First Law of thermodynamics, for CHP/HP systems rating and off-design operations. Indeed, an analytical method was designed along with the definition of a size factor. Then, a graphical method for coupling CHP and HP was presented so as to be an expeditious tool in designing phase. Finally, two numerical applications were illustrated highlighting the energy performance gains and the high level of operation flexibility.

1. Introduction

Nowadays, the need for efficient conversion technologies promotes the deployment of combined heat and power (CHP) production and heat pump (HP), accentuating their role in the energy systems. In terms of the hydraulics, these units are installed just like any conventional boiler to provide heat to the energy system, while, in the CHP case, there is the opportunity to generate electrical energy too. Such technologies can foster the diffusion of distributed generation systems, taking into account the conformation of the power grids [1–3].

As regards the CHPs, they have problems to meet efficiently the dynamic thermal energy demand depending on their technology. So, they are usually provided by a buffer system, e.g. a water tank [4]. In that behaviour, the CHP works at rated load so that to have a higher efficiency. At the same time, the electricity surplus should be sold to the grid, whether a net metering option is allowed, otherwise it should be stored locally. Selling to the grid could be uneconomical when the electricity price on the spot market is lower than the CHP generation cost, while it could be economically feasible if associated to an electric storage [5]. Many technologies, so-called Power-To-Power solutions, are already tested in this combination. Among those ones, Compressed Air Energy Storage (CAES) shows promising performance even hybridized with Phase Change Material [43] or coupling renewable generation with fossil-fuel one by means of synthetic fuel technology [44].

Furthermore, the CHP designed to meet the thermal energy demand implies to account for the matching between the CHP and end-user power to heat ratio as much as possible in order to increase the plant profitability.

Referring to HPs, they are a promising option to reduce the energy-related greenhouse gases emissions in the building and industrial sectors thanks to the use of freely available heat such as ambient air, water, ground and thermal cascade as well. In the building sector, the electrically driven air–water compression heat pumps (AWHP) are the most common technology for retrofits owing to their relatively low investment cost, easy installation and little required space [6]. Its drawback consists of a reduced efficiency as well as lower thermal output caused by low source medium temperatures and larger required temperature difference during the coldest period of the year. In the industrial sector, the choice of refrigerant plays a key role. Indeed, thermodynamic

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Nomenclature

CO_2	Carbon dioxide
$C_{E,f}$	CHP thermal generation cost [€/kWh]
C_{sys}	System capacity factor
$C_{sys,min}$	System capacity factor minimum value
$C_{TOT}(E_{in})$	Cost related to the overall inlet energy [€]
$C_{f,CHP}$	CHP capacity factor
$c_{f,HP}$	Capacity factor
c_w	Water specific heat [kJ/kg °C]
E134	Bis (difluoromethyl) ether
$E_{el,CHP}$	Electrical energy from CHP [kWh]
$E_{H,out}$	Total thermal energy from combined system [kWh]
f_s	Size factor
f'_s	Size factor in off-design operation
I_{el}	Power to heat ratio
K_1	Correction factor no.1
$K_{1,p}$	Correction factor accounting for primary energy
K_2	Correction factor no.2
K_3	Correction factor no.3
K_{el}	Correction factor accounting for electricity over-production
K_f	Efficiency correction factor
$\dot{m}_w$	Water mass flow rate [kg/s]
$\dot{m}_{pollutant}$	Pollutant mass flow rate [kg/s]
$P_{el,aux.}$	Auxiliary electrical power [kW]
$P_{el,CHP}$	CHP electrical power [kW]
$P_{el,exc.}$	Electrical power excess [kW]
$P_{el,HP}$	HP electrical power [kW]
P_{fuel}	CHP fuel consumption [kW_t]
$P_{heat,CHP}$	CHP thermal power [kW_t]
P_{HP}	HP thermal power [kW_t]
P_{Sink}	Heat sink thermal power [kW_t]
$P_{heat,HP}$	HP thermal power [kW_t]
$P'_{el,aux}$	Auxiliary electrical power in off-design operation (when the HP results oversized relative to CHP) [kW]
$P'_{el,exc}$	Electrical power excess in off-design operation [kW]
$P'_{el,HP}$	HP electrical power in off-design operation [kW]
P'_{HP}	HP thermal power at partial load [kW_t]
$P'_{heat,CHP}$	CHP thermal power at partial load [kW_t]
q_{fuel}	Fuel flow rate [Nm^3/s]
R22	Chlorodifluoromethane
R114	1,2-dichlorotetrafluoroethane
R141b	1,1-dichloro-1-fluoroethane
R143	1,1,2-trifluoroethane
R236ea	1,1,1,2,3,3-hexafluoropropane
R236fa	1,1,1,3,3,3-hexafluoropropane
R744	Carbon dioxide
T_{amb}	Outdoor temperature [°C]
$T_{exh,in}$	Exhaust gas inlet temperature [°C]
$T_{exh,out}$	Exhaust gas outlet temperature [°C]
$T_{in,HX}$	Heat exchanger water inlet temperature [°C]
$T_{out,HX}$	Water outlet temperature for end-user supplying [°C]
T_{sink}	Cold sink temperature for HP [°C]
ΔT_{SH}	Water temperature difference due to the CHP contribution for the end-user [°C]
$\Delta T_{w,HP}$	Water temperature difference due to the HP [°C]

Abbreviations

AEEG	Authority for electricity and natural gas (in italian)
AWHP	Air-Water compression heat pump
CHP	Combined heat and power
CHPR	Crossed heat to power ratio
CHPR'	Crossed heat to power ratio in off-design operation
COP	Coefficient of performance
EU	European union
GEHP	Gas engine-driven heat pump
GSHP	Ground source heat pump
HP	Heat pump
HPGHP	Hybrid-Power gas engine-driven heat pump
HVAC	Heating, ventilating and air conditioning
ICE	Internal combustion engine
LHV	Lower heating value [MJ/Nm^3]
NG	Natural gas
ORC	Organic rankine cycle
PV/T	Photovoltaics/Thermal
RES	Renewable energy sources
TOE	Tons of oil equivalent
TPF_{HP}	HP thermal power fraction
TPF_{CHP}	CHP thermal power fraction

Greek symbols

ε	Liquid-to-gas heat exchanger effectiveness
$\eta_{I,CHP}$	CHP first law efficiency
$\eta_{I,sys}$	First law efficiency related to the whole combined CHP/HP plant
$\eta_{I,sys(act)}$	Corrected first law efficiency related to the whole combined CHP/HP plant
η_{el}	CHP electrical efficiency
$\eta_{el,sys}$	Equivalent electrical system efficiency
η_{Grid}	Power grid efficiency
$\eta_{g,ref}$	Reference heat generator conversion efficiency
$\eta_{H,sys}$	Combined CHP/HP system efficiency for heating
$\eta_{H,sys(av)}$	Average combined CHP/HP system efficiency for heating
$\eta_{H,sys(act)}$	Actual combined CHP/HP system efficiency for heating
η_{hr}	CHP heat recovery efficiency
η_{REL}	Relative efficiency between distributed generation system and power grid
$\eta'_{I,sys(act)}$	Actual first law efficiency related to the whole combined CHP/HP plant in off-design operation
$\eta'_{H,sys(act)}$	Actual combined CHP/HP system efficiency for heating in off-design operation

properties, safety and transport issues promoted the use of refrigerants such as R744 (Carbon Dioxide), which could be used as coolant or in thermal cascade system [7,8]. This latter provides the opportunity to integrate large scale Heat Pump in recovering waste heat from existing thermal cycles.

Having said, the HPs represent a more efficient solution owing to their COP but they work at lower input-output temperature. As matter of fact, the recent deployment of Heat Pumps in replacing conventional systems such as boilers has raised many issues linked to the new adjustments required to the local electricity distributors. Indeed, the HP is an adjunct electrical demand which entails the upgrade of the end-users' electricity meter along with further transmission costs. For instance, in Italy the Authority for Electricity and Natural Gas (AEEG) imposes the purchase of a dedicated electricity meter for the HP installation [9]. So, considering the advantages of both CHP and HP technologies, a foreseeable solution could be their coupling to increase the overall energy efficiency for heating purposes as well as to reduce the associated CO_2 emissions.

1.1. Why investigating on CHP and HP coupling for heating plants

The substitution of energy system with new much more efficient one is a key issue in energy refurbishment of buildings and industrial processes. As a matter of fact, total substitution is often impossible. Furthermore, the on-off regulation widely used in the 20th century is so replaced with partial load conditions allowing reducing the downtime. However, load modulation for boilers as well as the reduced rotational speed of the engines usually corresponds to efficiency less than at rated load. For this reason, when old and new energy systems work at the same time, the overall efficiency decreases deeply compared to the declared one at rated conditions. So, civil and industrial applications require better system performance at partial load for each thermal machine to achieve a higher overall efficiency so as to reduce primary energy consumption. This latter, once measured in TOE (Tons of Oil Equivalent), is the main key performance indicator to develop energy management strategies. For instance, in energy refurbishment of public building stock, achieving goals of TOE reduction is driven by EU legislation [10]. To do so, Public Administrations are calling for thermal management services based on energy performance contracts where electric RES use is not allowed to get the primary energy saving. In this framework, the adoption of those combined systems would be able to accomplish the energy targets.

Specifically, a suitable matching of a CHP and a HP in the same energy system leads to higher efficiency, flexibility and safety along with deriving economic benefits. Few references are available in scientific literature about the combination of CHP and HP technologies. One of the first studies is related to a preliminary analysis showing the potential of a domestic scale hybrid CHP/HP plant in terms of energy utilisation, economic viability and emissions reduction [11]. Additionally, the incorporated heat pump gives a high degree of flexibility in meeting domestic energy requirements. Those considerations were confirmed by Smith et al. in a second study where demonstrated practically the advantages of heat-pump incorporation, giving an enhanced thermal delivery and higher total plant efficiency [12]. Then, from the exergy analysis carried out by the same authors [13], it emerged that by using an alternative refrigerant, operation at higher temperatures would reduce the exergy losses within the HP. In this framework, this paper analysed also the technical option of using the waste heat from CHP exhaust gases as a heat sink for the HP device. In the last decade, research projects focused on HP advances concluded that HP readily compliment with many renewable energy technologies to produce desired heat and power at reduced basic fuel input, in cogeneration design [14]. For instance, in small-scale distributed applications HP coupled CHP showed energy saving and emission reduction up to 50% compared to conventional layout [15]. From an energy point of view, the combined CHP/HP system is equivalent to the well-known GEHP (Gas Engine driven Heat Pump), where the CHP electrical output matches perfectly the HP electric demand within a unique block. Several studies investigated on different GEHP layouts and their performance along with the comparison with HPs [16]. Considering the device behaviour during transients, under a constant speed operation, GEHPs are more efficient than electric HPs, while HPs are more efficient under variable speed operations [17]. Hence, both HPs and GEHPs are remarkably influenced by the engine speed. Anyway, GEHPs are more energy efficient in the low speed mode [18]. The unique block architecture entails a unique energy output, i.e. thermal. On the contrary, the CHP and HP connection by the Grid offers the opportunity to provide electricity during the thermal load modulation from end-user side. The advantage of the combined system consists of HPs operational flexibility throughout a varying load profile, by maintaining high coefficient-of-performance (COP) values [19]. This latter feature, i.e. a "quantitative" flexibility, is so important that some

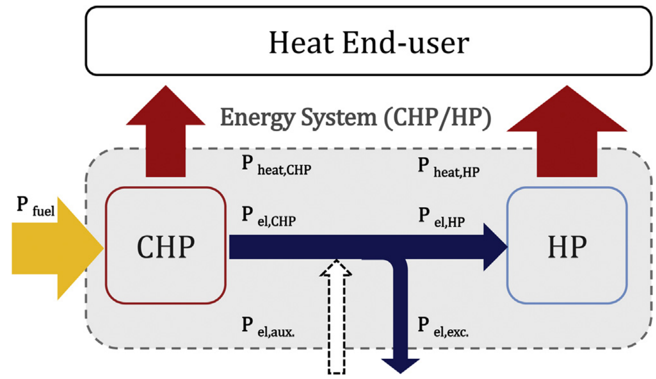

Fig. 1. Energy flows of combined CHP and HP system.

research activities focused on modifying the GEHP basic layout by adopting the hybridization concept from electric motor-assisted engines. Li et al. studied a HPGHP (Hybrid-Power Gas engine-driven Heat Pump) system where the electric output is stored in a battery-pack to assist the ICE at low rotational speed [20], increasing its thermal efficiency at partial load.

Moreover, a combined system is able to provide high and low temperature heat, simultaneously. Therefore, another significant aspect regards the "qualitative" flexibility. The option to provide only high grade temperature is also available by the use of double-stage electric HP or Trans critical Carbon Dioxide-based HPs [21], where the Heat sink is not a RES. Cutting-edge applications focus on fuel supply-side, involving eco-fuels such as Hydrogen or its mixtures [22,23]. Whether Power to Gas option was considered, well-proven technologies could be fuelled with environmentally-friendly fuels without heavy technical issues [24,25]. Differently, a shift towards Hydrogen economy requires a further effort, i.e. the deployment of Fuel Cell technologies that are already studied in literature for Heat Pump coupling [26,27]. Additionally, another interesting feature of a system composed of different appliances is to decrease the size of them so that to simultaneously match minor safety requirements. For instance, power plants up to 3 MW of heat produced in the firebox of the boiler need a continuous monitoring system for pollutant emissions [28]. As aforementioned, a coupled system (CHP + HP) could use the electricity production of the CHP to feed the HP so that to avoid the upgrade of the transformer kiosk and deriving costs. Those latter issues were the focus of recent research in formulating electrical-equivalent load following strategy superior than conventional strategies from both economic and energetic point of view, better load coincidence and peak reduction, respectively [45].

Thus, as purpose, this work is focused on the following points:

i coupling two well-established technologies: a CHP and a HP (presenting a graphical method). This configuration could represent a viable solution to support the energy retrofitting;
ii an analytical method was designed and an oversize/downsize factor was defined due to the mismatch between the power sizes of the two appliances available on the market as well as the deriving technical issues;
iii the system efficiency was discussed for these more complex plants.

2. Energy system model

In this section, the reference energy model was presented. It is composed of a CHP and a HP which are electrically connected by the local grid. As depicted in Fig. 1, both CHP and HP thermal power outputs were released to the end-user. As regards the CHP electrical output, it could feed the HP partially or totally, depending on the machines size and the operating conditions at rated and partial loads required by the end-user. Those coupling issues are the core of the present investigation. In details, the authors limited the investigation on the heating mode because heating is the common output of HP and CHP production. A different discussion should be conducted on the cooling mode owing to a further heat conversion of the CHP output to accomplish cooling purposes. In that case, new components such as adsorption chiller or reversible HP are required along with the introduction of other key parameters, i.e. Energy Efficiency Ratio for the HP and a Power To Cooling Ratio (PTCR) for the end-user. So, it is crucial to make an energy-economic analysis to choose between a new integrated conversion process, i.e. the adsorption cycle, and the direct use of the CHP thermal output into the existing Air Treatment Unit for post-heating exchangers. Finally, considering both summer and winter seasons entails another primary energy analysis to size properly the CHP and HP but, the authors aim to provide a simplified procedure to the HVAC technicians by using few inputs to describe the entire system. Referring to the system primary energy consumption, two kinds of inputs are considered: a direct input, in terms of fuel units to feed the CHP, and an indirect one, in terms of auxiliary electricity to supply the complementary HP need, when it is not completely covered by the engine power production.

Starting from this functional scheme and using the common peculiar parameters of each machine, the aim of this paper is to formulate a simple model, based on the First Law of Thermodynamics, elaborating different maps to assess the efficiency for heating purposes. A specific focus is set on the operational flexibility in off-design conditions.

3. Perfect coupling and design conditions

CHP technologies can be identified immediately by the numerical values of three meaningful parameters: electrical efficiency, heat recovery efficiency and Power to Heat Ratio, which are reported below, respectively.

$$\eta_{el} = \frac{P_{el,CHP}}{P_{fuel}} \quad (1a)$$

$$\eta_{hr} = \frac{P_{heat,CHP}}{P_{fuel}} \quad (1b)$$

$$I_{el} = \frac{P_{el,CHP}}{P_{heat,CHP}} = \frac{\eta_{el}}{\eta_{hr}} \quad (1c)$$

Similarly, the HPs are distinguished by the Coefficient Of Performance, which depends on load control technology and outdoor temperature, as follows:

$$COP = f(P_{HP}, T_{sink}) = \frac{P_{HP}}{P_{el,HP}} \quad (2)$$

Here, the Crossed Heat to Power Ratio was defined as HP thermal output divided by CHP electrical output:

$$CHPR = f\left(P_{HP}, T_{sink}, P_{el,CHP}\right) = \frac{P_{HP}}{P_{el,CHP}} \quad (3)$$

Therefore, the combined system efficiency for heating can be calculated as:

$$\eta_{H,sys} = \frac{P_{heat,CHP} + P_{HP}}{P_{fuel}} \quad (4)$$

Assuming $P_{el,CHP}$ equal to $P_{el,HP}$, Eq. (4) can be rearranged by substituting Eqs. (1a)–(3) and the combined system efficiency for heating reads as:

$$\eta_{H,sys} = \eta_{hr} \cdot (1 + COP \cdot I_{el}) \quad (5)$$

It is a function directly proportional to the CHP heat recovery efficiency, the Coefficient of Performance and the Power to Heat Ratio. For instance, considering a CHP characterized by η_{hr} and I_{el} equal to 0.5 and 0.6, respectively, and a HP with a COP equal to 3.5, $\eta_{H,sys}$ results in 1.55. This value compared to a usual condensing boiler, i.e. 1.05, can be higher of 50 percentage points and it is referred directly to primary energy consumption. From this comparison, it emerges that the combined system represents an attractive solution for heating purposes. However, the simple electrical HPs seem to be more efficient due to their higher conversion performance but this value is not related to the primary energy consumption. In order to assess to actual competitiveness of the combined system respect to a HP, the Power Grid efficiency should be considered and the inequality reads as:

$$\eta_{H,sys} \geq COP \cdot \eta_{Grid} \quad (6)$$

Eq. (6) provides the Power Grid efficiency threshold to make profitable the combined system. By substituting the previous numerical values, η_{Grid} is equal to 0.443. It entails that in Countries with very high η_{Grid} such as United Kingdom, the HPs are more convenient than the combined system. In all other cases, this latter is the best solution. Referring to the current average Power Grid efficiency worldwide, i.e. 0.385, the CHP+HP layout appears as a viable solution today and in the next 20 years, assuming a future η_{Grid} equal to 0.42 [29].

3.1. The map tool

A graphical tool is provided to help designers in performance assessment and retrofitting strategies by means of installing combined systems. Starting from Eq. 5, three charts were elaborated to correlate directly the machines parameters with the overall efficiency for heating. They could be used by the following procedure listed below and the logical pathway is depicted in Fig. 2:

- Once a CHP technology is chosen by its own electrical and heat recovery efficiency, in chart a), at bottom-left of Fig. 2, it is possible to insert the CHP electrical efficiency, to intercept the relative CHP heat recovery curve so that to determine the Power to Heat Ratio reciprocal.
- Then, this latter is the input value for chart b), at bottom-right of the same Figure. This chart is related to the HP choice by means of its COP. Indeed, having inserted the Power to Heat Ratio reciprocal and chosen the HP, COP multiplied by I_{el} is calculated.
- Finally, in chart c), at top-right of the Figure, the vertical interception with the CHP heat recovery efficiency curve provides the combined system efficiency for heating.
- In addition, chart d), at top-left of the Figure, is provided by the authors to correct $\eta_{H,sys}$ in order to account for machines electrical size mismatch due to the availability of merchandised models by a dedicated coefficient, calculated in the next sections.

The mismatch issue will be deeply investigated in Section 4.

In order to facilitate the use of the maps, they were divided in Figs. 3 and 4. Specifically, the second part of the map, as shown in Fig. 4, consists of the bottoming chart built in semi-logarithmic scale, while the topping one in logarithmic scale. This representation was due to make them readable and usable for the readers. Indeed, without the logarithmic axis the $COP \cdot I_{el}$ values between 0.1 and 1 were not measurable. The same is valid for the topping chart related to $\eta_{H,sys}$.

For starting the analysis, a table summarizing all the typical electrical and heat recovery efficiency values of CHP systems categorized by their own technology is provided below. Table 1 reads as:

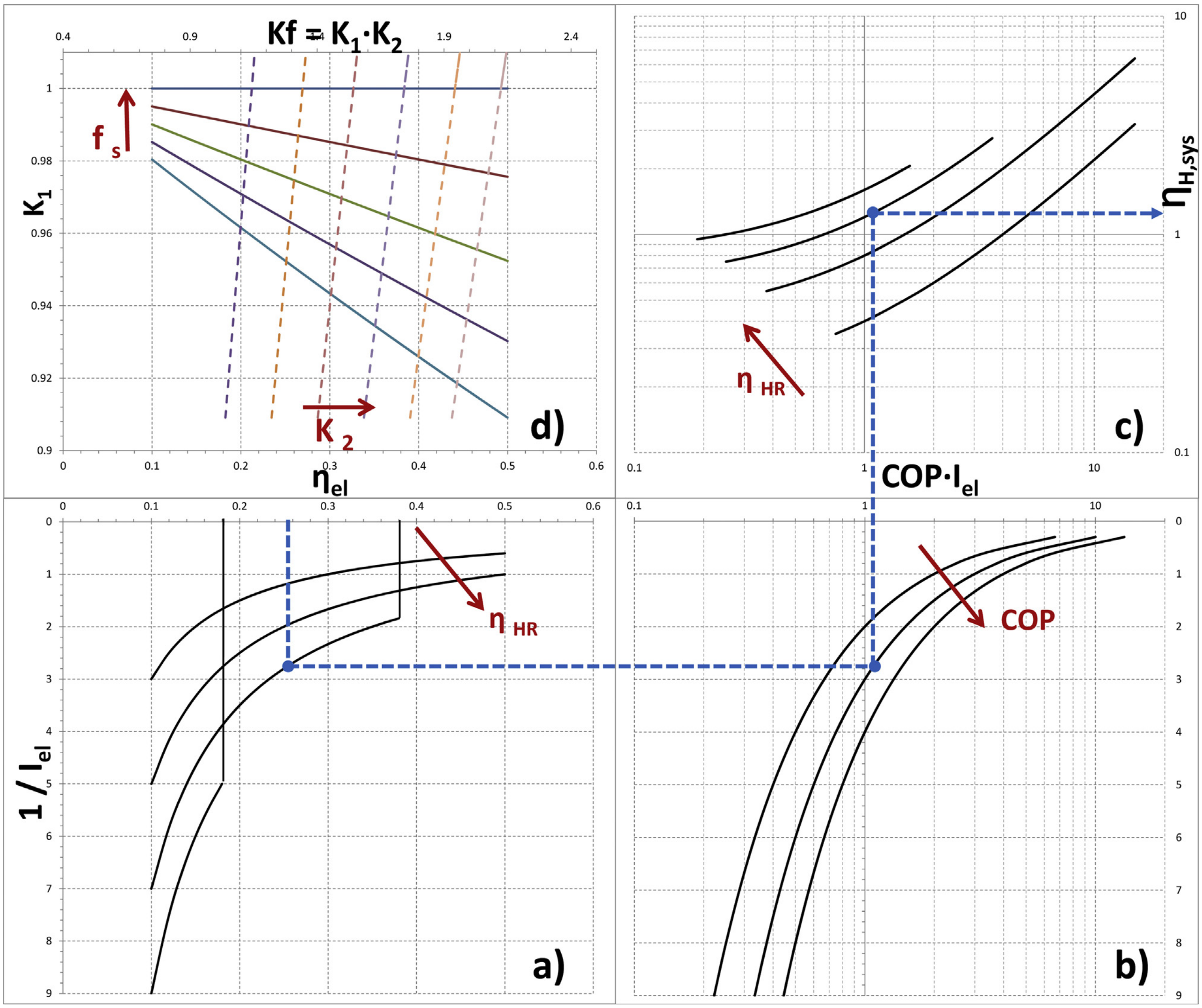

Fig. 2. Graphical procedure to use the map.

Table 1
CHP electrical and heat recovery efficiency per technology type.

CHP Technology	η_{el}	η_{hr}	First Law Efficiency	I_{el}	References
Internal Combustion Engine	0.2–0.4	0.3–0.5	0.5–0.9	4–0.8	[30,31]
Internal Combustion Engine (condensing heat exchanger)	0.26–0.32	0.74–0.76	1–1.08	0.35–0.42	[32]
Micro Gas Turbine	0.25–0.3	0.5–0.55	0.75–0.85	0.5–0.54	[31,33,34]
Gas Turbine	0.15–0.42	0.32–0.55	0.47–0.97	0.47–0.76	
Steam Turbine (back pressure)	0.15–0.25	0.6–0.7	0.75–0.95	0.25–0.35	
Steam Turbine (condensing)	0.32–0.38	0.32–0.55	0.64–0.93	1–0.7	
Fuel Cell PEM	0.3–0.4	0.55–0.5	0.85–0.9	0.54–0.8	[31,33–35]
Fuel cell Solid Oxide	0.4–0.6	0.35–0.25	0.75–0.85	1.14–2.4	[31,33–35]

4. Energy effects related to the size mismatch between commercial CHP and HP

The CHP and HP perfect power coupling does not occur very often, due to the machines commercial size available on the market. In order to assess the combined system energy penalties and gains caused by the contingent electrical power mismatching, an oversize/downsize factor was defined in Eq. (7), below:

$$f_s = \frac{P_{el,HP}}{P_{el,CHP}} \tag{7}$$

Since the consumed electrical power by the heat pump can be deduced from COP equation, the size factor can correlate directly the CHPR with the COP as follows:

$$f_s = \frac{P_{HP}}{\left(P_{el,CHP} \cdot COP\right)} = \frac{CHPR}{COP} \tag{8}$$

Assuming $f_S \geq$, it entails that auxiliary electrical power from the grid is required in order to produce the rated HP thermal power output. It affects the theoretical system efficiency as shown in Eq. (9):

$$\eta_{H,sys} = \frac{P_{heat,CHP} + P_{HP}}{P_{fuel} + P_{el,aux}} \tag{9}$$

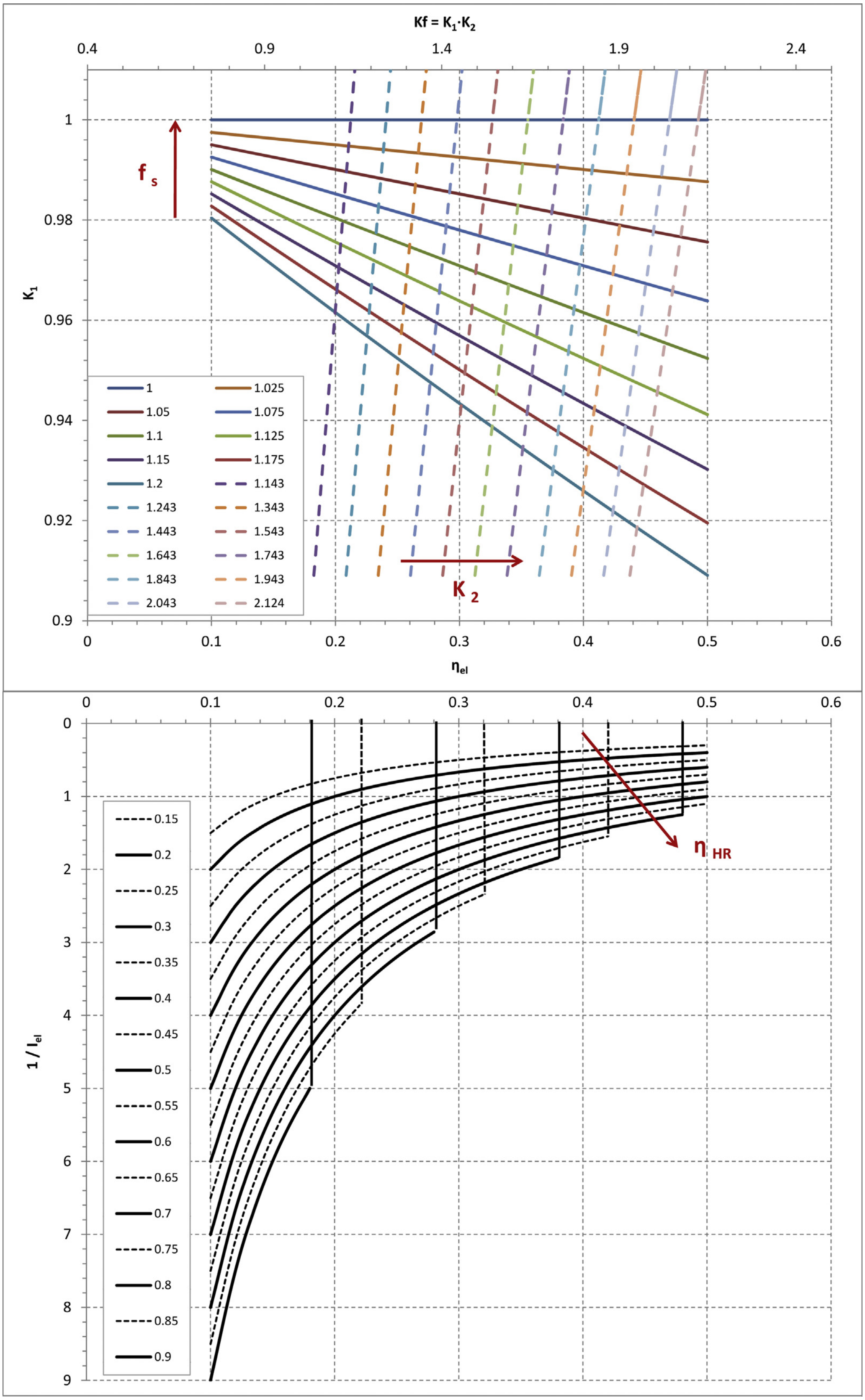

Fig. 3. First half of the map to calculate the Power to Heat Ratio reciprocal and Correction Factors.

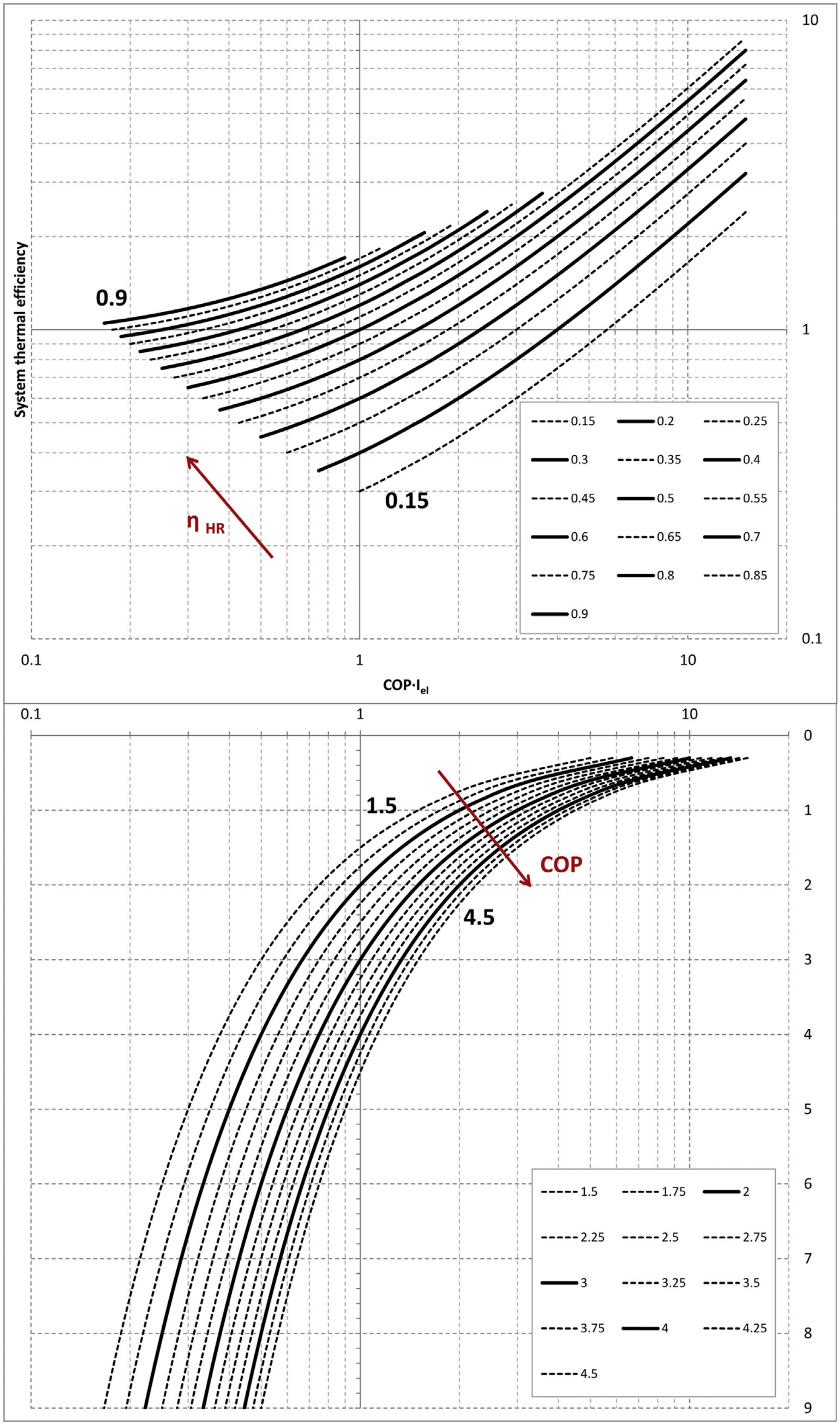

Fig. 4. Second half of the map to calculate COP multiplied by I_{el} and combined system thermal efficiency.

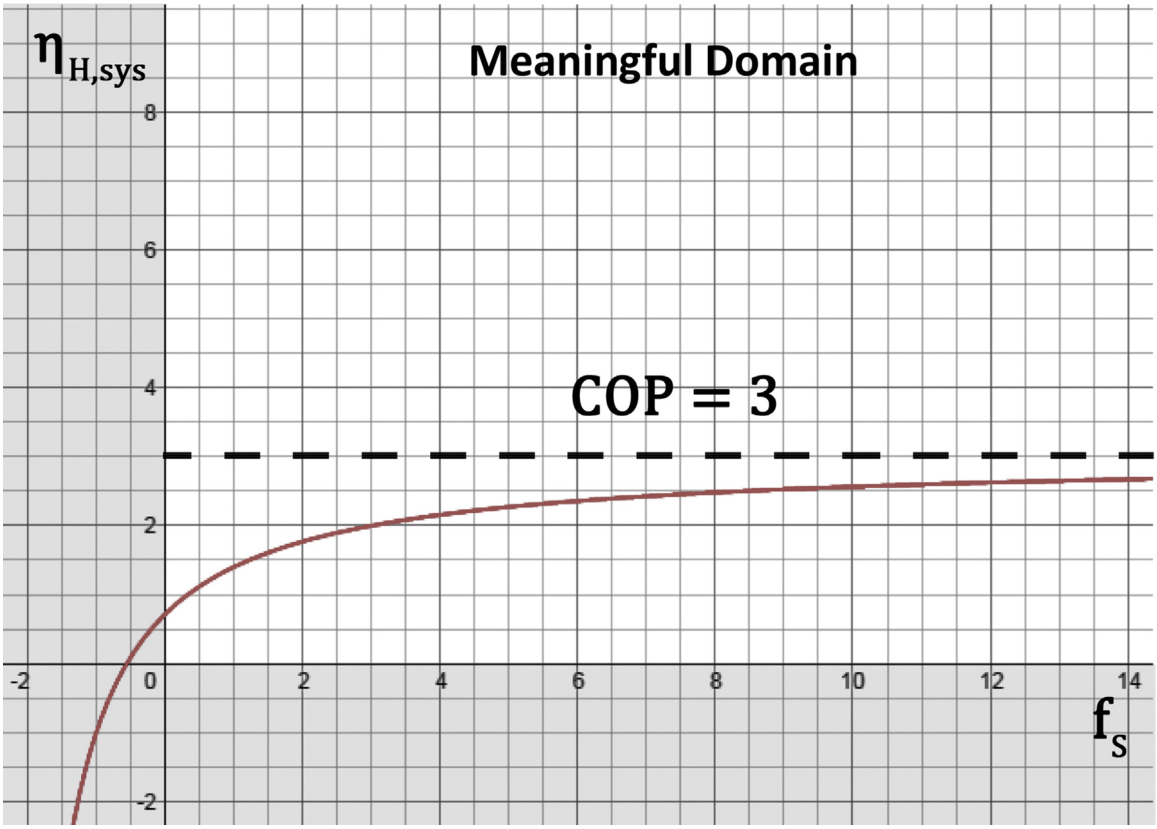

Fig. 5. The combined system efficiency for heating vs. the size factor. Assumptions for calculation: COP = 3; η_{el} = 0.3; η_{hr} = 0.5.

Here, $P_{el,aux}$ denotes the difference between HP electricity consumption and CHP electricity production:

$$P_{el,aux} = \left(P_{el,HP} - P_{el,CHP}\right) = (f_s - 1) \cdot P_{el,CHP} \tag{10}$$

Rearranging all of terms, the actual system efficiency, accounting for the sizes mismatch, is reported below:

$$\eta_{H,sys(act)} = \frac{\eta_{hr} \cdot (1 + CHPR \cdot I_{el})}{1 + (f_s - 1) \cdot \eta_{el}} \tag{11}$$

The system thermal efficiency as a function of the oversize factor f_S is reported in Fig. 5.

From an analytical point of view, red line represents an equilateral hyperbole. It is noteworthy that only the white section of Fig. 5 is physically meaningful. When the size factor increases, the system efficiency increases in asymptotic fashion as well, up to a limited value equal to COP as shown in Eq. (12):

$$\lim_{f_s \to \infty} \frac{\eta_{hr} \cdot (1 + f_s \cdot COP \cdot I_{el})}{1 + (f_s - 1) \cdot \eta_{el}} = COP \tag{12}$$

It is possible to account for the thermal efficiency changes, owing to the machines size mismatching, by means of the maps of the machines perfect coupling, directly. Thereafter, the final value can be calculated multiplying by an efficiency correction factor. It was defined as:

$$K_f = \frac{\eta_{H,sys(act)}}{\eta_{H,sys}} \tag{13}$$

As a consequence, the actual combined system efficiency for heating reads as:

$$\eta_{H,sys(act)} = \eta_{H,sys} \cdot \left(\frac{1}{1 + (f_s - 1) \cdot \eta_{el}}\right) \cdot \left(\frac{1 + CHPR \cdot I_{el}}{1 + COP \cdot I_{el}}\right) \tag{14}$$

Then, two factors can summarize the two parts of Eq. (14), as shown below:

$$K_1 = \left(\frac{1}{1 + (f_s - 1) \cdot \eta_{el}}\right) \tag{15}$$

$$K_2 = \left(\frac{1 + CHPR \cdot I_{el}}{1 + COP \cdot I_{el}}\right) \tag{16}$$

The correction factor K_f results in a simplified expression:

$$K_f = K_1 \cdot K_2 \tag{17}$$

In Fig. 6, K_2 can be deduced once f_S value is fixed as well as $COP \cdot I_{el}$. Furthermore, Fig. 7 provides the value of K_f, having introduced the CHP electrical efficiency, intercepted the corresponding f_S curve and the K_2 one.

Referring to primary energy, the auxiliary electrical power can be converted directly into the required thermal power once the Power Grid average efficiency (i.e. η_{Grid}) is known. Under this hypothesis the overall system efficiency reads as:

$$\eta_{H,sys(act)} = \frac{\eta_{hr} \cdot (1 + CHPR \cdot I_{el})}{1 + (f_s - 1) \cdot \eta_{REL}} \tag{18}$$

Where Eq. (19) denotes the relative efficiency between distributed generation system and Power Grid:

$$\eta_{REL} = \eta_{el} / \eta_{Grid} \tag{19}$$

In that case, the correction factor can be modified as follows:

$$K_f = K_{1,p} \cdot K_2 = K_1 \cdot K_2 \cdot K_3 \tag{20}$$

Here, the new coefficient K_3 is reported below:

$$K_3 = \frac{K_{1,p}}{K_1} = \frac{\eta_{Grid} \cdot [1 + (f_s - 1) \cdot \eta_{el}]}{\eta_{Grid} + (f_s - 1) \cdot \eta_{el}} \tag{21}$$

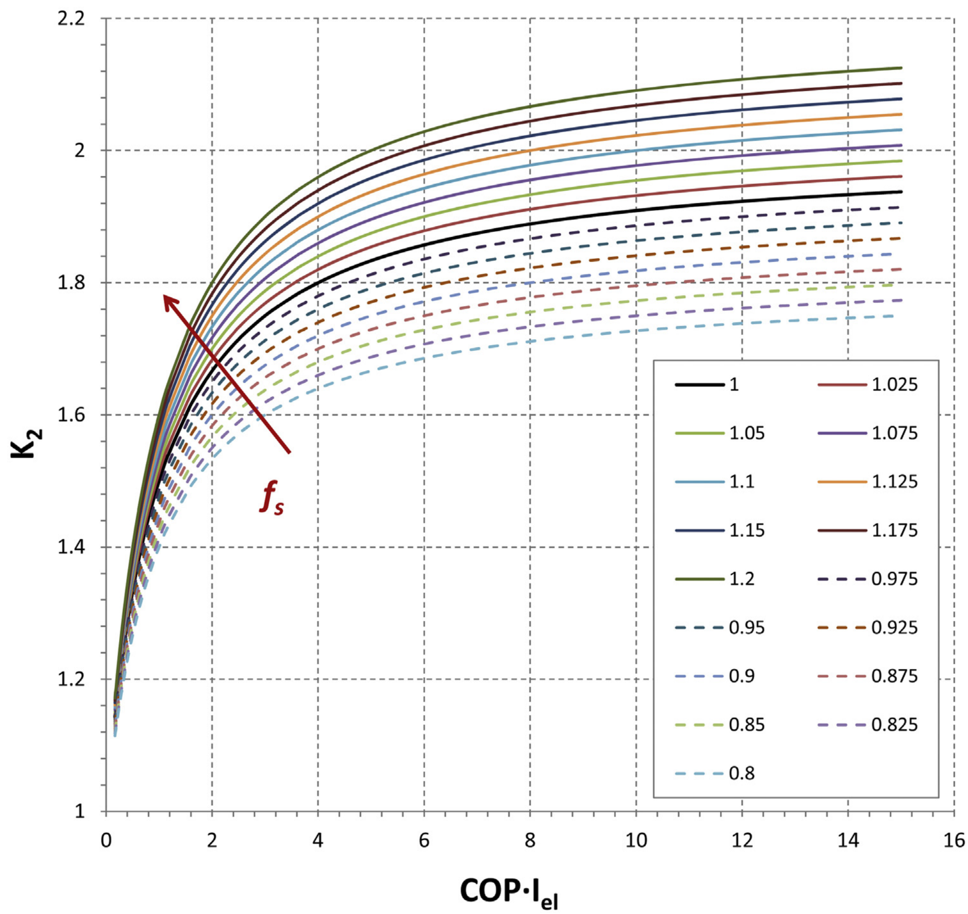

Fig. 6. K_2 coefficient vs. COP · I_{el} with changes in over/downsize factor.

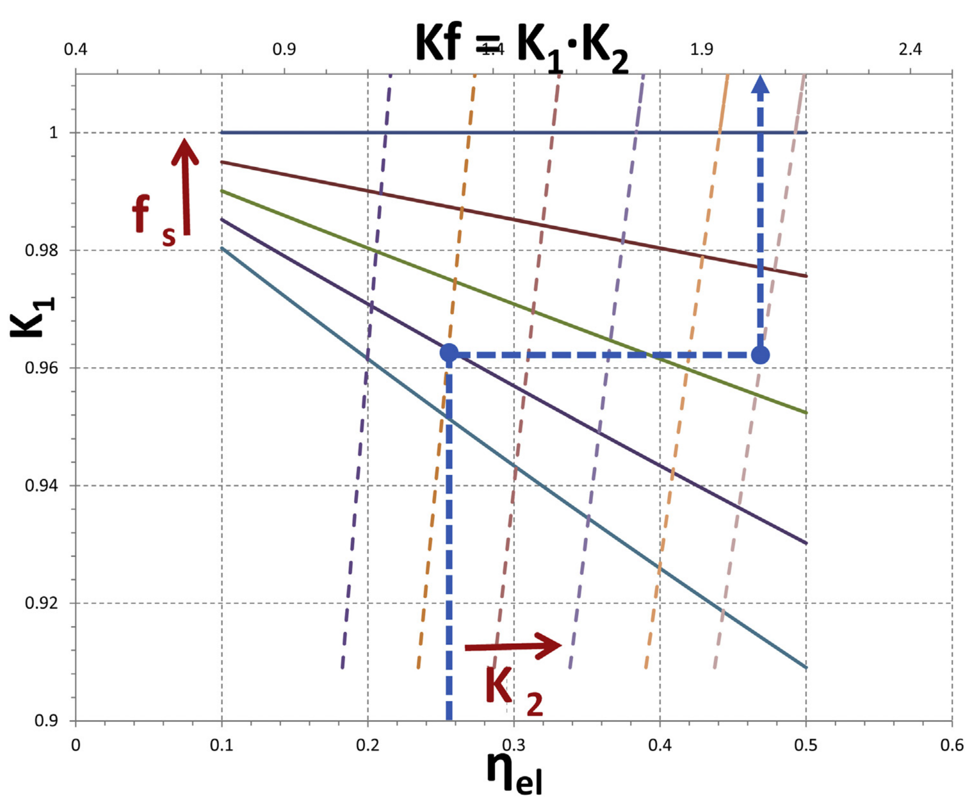

Fig. 7. Procedure for Correction Factor calculation.

Moreover, when the oversize factor increases, Eq. (12) is limited by the COP·η_{Grid} product.

Considering the HP downsizing effect (i.e. $P_{el,HP} < P_{el,CHP}$) the system energy balance changes owing to an electricity excess occurrence. In that case the size factor can be lower than unity and the electricity excess is reported in Eq. (22):

$$P_{el,exc} = P_{el,CHP} - P_{el,HP} = (1 - f_s) \cdot P_{el,CHP} \tag{22}$$

Substituting Eq. (22) within the general expression for the overall thermal efficiency, it reads as follows:

$$\eta_{H,sys(act)} = \eta_{hr} \cdot (1 + f_s \cdot COP \cdot I_{el}) \tag{23}$$

Similarly, the correction factor for $f_S < 1$ can be expressed by:

$$K_f = \frac{\eta_{H,sys(act)}}{\eta_{H,sys}} = \left(\frac{1 + CHPR \cdot I_{el}}{1 + COP \cdot I_{el}}\right) = K_2 \tag{24}$$

In addition, taking into account the electrical power output overproduction, it is possible to state that the system thermal efficiency corresponds to the First Law efficiency related to the whole combined CHP + HP plant, as in Eq. (25):

$$\eta_{I,sys(act)} = \eta_{H,sys(act)} + \eta_{el,sys} \tag{25}$$

The equivalent electrical efficiency of the whole system is:

$$\eta_{el,sys} = (1 - f_s) \cdot \eta_{el} \tag{26}$$

Thereafter, the correction factor can be modified as follows:

$$K_f = \frac{\eta_{I,sys(act)}}{\eta_{H,sys}} = \frac{[(1 + CHPR \cdot I_{el}) + (1 - f_s) \cdot I_{el}]}{1 + COP \cdot I_{el}} = (K_2 + K_{el}) \tag{27}$$

A new coefficient K_{el} is introduced as reported in Eq. (28):

$$K_{el} = \frac{(1 - f_s) \cdot I_{el}}{1 + COP \cdot I_{el}} \tag{28}$$

4.1. Off-design operation of the combined heating system at partial load

The contributions of each system component to the overall thermal power output were defined by the thermal power fractions as reported below:

$$TPF_{HP} = \frac{f_s \cdot COP \cdot \eta_{el}}{\eta_{H,sys(act)}} \tag{29}$$

$$TPF_{CHP} = \frac{\eta_{hr}}{\eta_{H,sys(act)}} \tag{30}$$

Eq. (29) describes the HP thermal power fraction while, Eq. (30) the CHP one. So, the thermal power ratio between HP and CHP can be easily calculated by Eq. (31):

$$\frac{P_{HP}}{P_{heat,CHP}} = \frac{TPF_{HP}}{TPF_{CHP}} = f_s \cdot COP \cdot I_{el} \tag{31}$$

From this latter it emerges that COP·I_{el} value is a characteristic parameter for combined system design.

Then, the partial load conditions for both HP and CHP were modelled. As regards the HP, the definition of its partial load is reported in Eq. (32):

$$P'_{HP} = c_{f,HP} \cdot P_{HP} \tag{32}$$

Assuming $0 \le c_{f,HP} \le 1$, it represents the heat pump capacity factor. Two situations can occur:

- the COP depends only on cold sink temperature if the HP is equipped with the inverter regulation technology;
- the COP depends on both cold sink temperature and required thermal load.

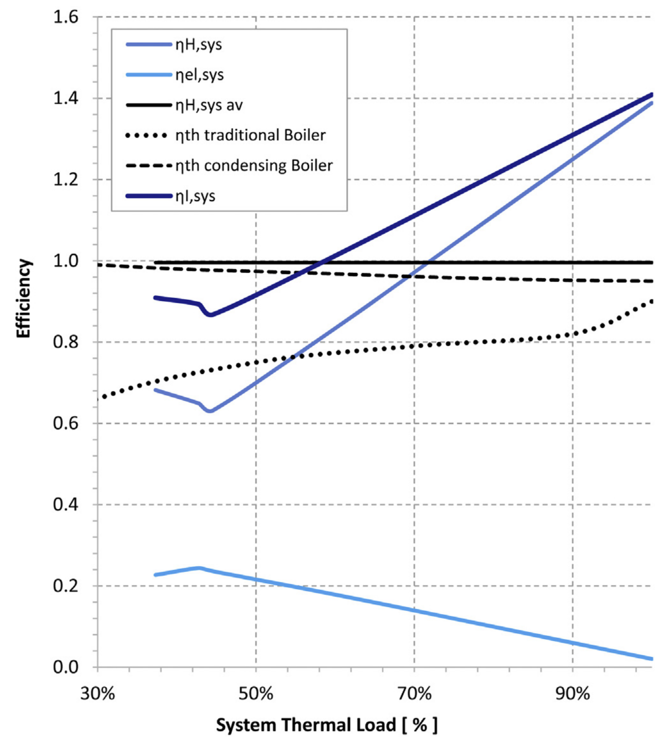

Fig. 8. Comparison between CHP/HP system and conventional heating solutions with changes in thermal loads. CHP = 5 kW_{el}/HP = 16 kW_{th}.

In the first case, a first approximation to calculate the COP can be found in literature, where it is expressed as an ascending linear function of the cold sink temperature for air-to-air HPs [36] and it is a rising polynomial curve for air-to-water ones [37]. In the second case, the characteristic curves of each HP technology should be considered. The calculated value of the COP will be inserted within the maps. In this study, due to their widespread use, the authors considered the first mentioned typology IDHP, i.e. Inverter Driven Heat Pump.

Referring to the CHP, its definition of partial load reads as:

$$P'_{heat,CHP} = c_{f,CHP} \cdot P_{heat,CHP} \tag{33}$$

It is remarkable that at partial load the recoverable heat decreases with a reduced rotational speed of the engine notwithstanding the heat recovery efficiency increases due to higher recoverable energy losses, as demonstrated in experimental campaign from literature [32].

Therefore, the whole system capacity factor can be defined as follows:

$$C_{sys} = c_{f,HP} \cdot TPF_{HP} + c_{f,CHP} \cdot TPF_{CHP} \tag{34}$$

When the heat pump results oversized relative to CHP, the auxiliary electrical power from the grid tends to decline as lower is the heat pump capacity factor.

$$P'_{el,aux} = \left(P'_{el,HP} - P_{el,CHP}\right) = \left(c_{f,HP} \cdot f_s - 1\right) \cdot P_{el,CHP} \tag{35}$$

When the size factor is higher than unity, the system thermal efficiency variation, due to the HP load reduction, is reported below, assuming that COP is constant with varying thermal power output, thanks to the inverter regulation system application:

$$\eta'_{H,sys(act)} = \frac{P_{heat,CHP} + P'_{HP}}{P_{fuel} + P_{el,aux}} = \frac{COP \cdot c_{f,HP} \cdot P_{el,HP} + P_{heat,CHP}}{P_{fuel} + (f_s - 1) \cdot P_{el,CHP}} \tag{36}$$

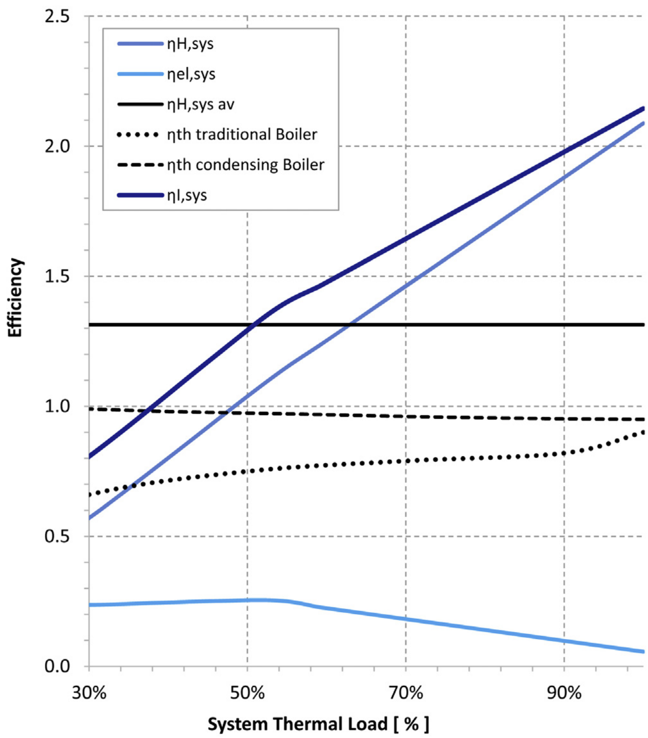

Fig. 9. Comparison between CHP/HP system and conventional heating solutions with changes in thermal loads. CHP = 60 kW_{el}/HP = 250 kW_{th}.

Rearranging all of terms, the final expression for the system efficiency calculation at partial load conditions was given in Eqs. (37) and (38):

$$\eta'_{H,sys(act)} = \frac{\eta_{hr} \cdot \left(1 + c_{f,HP} \cdot COP \cdot f_s \cdot I_{el}\right)}{1 + \left(c_{f,HP} \cdot f_s - 1\right) \cdot \eta_{el}}; \frac{1}{f_s} < c_{f,HP} \le 1 \quad (37)$$

$$\eta'_{H,sys(act)} = \eta_{hr} \cdot \left(1 + c_{f,HP} \cdot COP \cdot f_s \cdot I_{el}\right); 0 \le c_{f,HP} \le \frac{1}{f_s} \quad (38)$$

When the thermal load has to be further reduced, it is possible to decrease the CHP rotational speed or to enhance the resisting torque to the engine shaft and, consequently, the recovered heat by the heat exchangers. In this case, the system thermal efficiency variations are equal to those related to the CHP heat recovery efficiency, as in Eq. (39):

$$\eta'_{H,sys(act)} = \eta_{hr} = f\left(P'_{el,CHP}\right) \quad (39)$$

Using the same approach, it was possible to define similar equations related to the size factor lower than unity. The CHP electrical power overproduction tends to increase when the heat pump capacity factor declines as shown in Eq. (40).

$$P'_{el,exc} = P_{el,CHP} - P'_{el,HP} = \left(1 - f_s \cdot c_{f,HP}\right) \cdot P_{el,CHP} \quad (40)$$

Consequently, the overall thermal efficiency at partial load reads as:

$$\eta'_{H,sys(act)} = \eta_{hr} \cdot \left(1 + c_{f,HP} \cdot f_s \cdot COP \cdot I_{el}\right) \quad (41)$$

And, similarly, for the First Law efficiency, the expression is:

$$\eta'_{I,sys(act)} = \eta_{hr} \cdot \left[\left(1 + c_{f,HP} \cdot f_s \cdot COP \cdot I_{el}\right) + \left(1 - f_s \cdot c_{f,HP}\right)\right] \quad (42)$$

It is noteworthy that all of developed maps and their correction factors can be used also for assessing the combined system behaviour at partial load conditions. In fact, the equations related to the off-design operation have the same analytical form of the rated ones, when the following substitutions have been done:

$$f'_s = f_s \cdot c_{f,HP}; CHPR' = f'_s \cdot COP \quad (43)$$

Finally, the average efficiency value of the combined system over the regulation span can be evaluated by:

$$\eta_{H,sys(av)} = \frac{1}{1 - C_{sys,min}} \int_{C_{sys,min}}^{1} \eta_{H,sys(act)}(C_{sys}) dC_{sys} \quad (44)$$

In Table 2, the equations for each system type and operating conditions as well were summarized in a systemic overview.

5. Case studies

In this section, a numerical simulation is provided to evaluate the energy and environmental benefits coming from the use of the combined system compared with the conventional ones, (i.e. condensing boiler and traditional boiler) by means of the elaborated method. In detail, partial heating loads ranging from 30% up to 100% were evaluated using data from experimental campaign on CHPs carried out by the authors previously [23,32,38,39].

In Table 3, the measured CHP electrical and heat recovery efficiencies of two CHPs are summarized to build the partial load profile of the combined systems. The first condensing CHP with an electrical power output equal to 5 kW_{el} and I_{el} of 0.357, typical for dwellings application, was combined with a HP with a thermal output equal to 16 kW_{th} and a COP of 3.5. The second CHP with an electrical power output equal to 60 kW_{el} and I_{el} of 0.536, typical for small industrial application, was coupled with a HP with a thermal output equal to 250 kW_{th} and a COP of 5.

Furthermore, in both cases the f_S is lower than unity and equal to 0.914 and 0.833, respectively. Consequently, an electricity excess occurs and the system can be considered an equivalent large CHP. Then, in Table 4 the capacity factor of the combined system, i.e. C_{sys}, was calculated for different values of thermal load modulation, according to Eq. (34). Specifically, it represents regulation logic where priority is given to HP due to its constant performance at partial loads up to 30% of HP rated one. From this latter value, the CHP starts working in off-design up to the minimum admissible load of a general heating plant, around 30%.

In Fig. 8, the outcomes related to the first case study are presented. The combined system appears more efficient than the conventional boilers. Its efficiency in terms of heating is higher than 100% for partial loads up to 70%. Considering the First Law efficiency, good performance can be achieved up to 57%. In the second case study, as depicted in Fig. 9, CHP/HP is more efficient than the conventional boilers for partial loads up to 47%. It implies that the coupled CHP can work at rated load for a wide range of thermal energy demand reduction. All those comparisons were made by considering the fuel Lower Heating Value (LHV).

6. Concluding remarks

Civil and industrial sectors require better system performance for the heat generation at either rated and partial load for each thermal machine [40]. Referring to existing and older plants, effective retrofitting solutions are required to achieve higher overall efficiency so as to reduce primary energy consumption as ratified by recent European Directives. In this framework, a suitable matching of a CHP and a HP leads to higher performance, flexibility and safety along with deriving economic benefits [41,42]. For these reasons, simple and quick calculation tools were developed herein in order to support designers during the assessment process for plants refurbishment and new construction as well.

Table 2
Efficiencies equation overview for rated and off-design system operating conditions.

Efficiency	f_s			
	1	>1		<1
	$c_{f,HP} \leq 1$	$\frac{1}{f_s} < c_{f,HP} \leq 1$	$0 \leq c_{f,HP} \leq \frac{1}{f_s}$	$c_{f,HP} \leq 1$
$\eta_{H,sys}$	$\eta_{hr} \cdot \left(1 + c_{f,HP} \cdot CO \cdot I_{el}\right)$	$\frac{\eta_{hr} \cdot (1+COP \cdot f'_s \cdot I_{el})}{1+(f'_s-1) \cdot \eta_{el}}$	$\eta_{hr} \cdot (1 + COP \cdot f'_s \cdot I_{el})$	$\eta_{hr} \cdot (1 + f'_s \cdot COP \cdot I_{el})$
$\eta_{el,sys}$	$\left(1 - c_{f,HP}\right) \cdot \eta_{el}$	0	$(1 - f'_s) \cdot \eta_{el}$	$(1 - f'_s) \cdot \eta_{el}$
$\eta_{I,sys}$	$\eta_{H,sys} + \eta_{el,sys}$	$\frac{\eta_{hr} \cdot (1+COP \cdot f'_s \cdot I_{el})}{1+(f'_s-1) \cdot \eta_{el}}$	$\eta_{H,sys} + \eta_{el,sys}$	$\eta_{H,sys} + \eta_{el,sys}$

Table 3
CHP electrical and heat recovery efficiency from experimental campaign in [23,32,38,39].

Condensing micro CHP (prototype)			Commercial CHP (Valmet)		
Engine characteristics: - Naturally aspirated 499 cm^3 - Feeding system: electronic injection - Rotational speed: 1500–2100 rpm - $P_{el,CHP}$ = 5 kW; $P_{heat,CHP}$ = 14 kW - Operating ΔT = 52 °C–35 °C			Engine characteristics: - Naturally aspirated 7400 cm^3 - Feeding system: carburetor - Rotational speed: 1500 rpm - $P_{el,CHP}$ = 60 kW; $P_{heat,CHP}$ = 112 kW - Operating ΔT = 70 °C–58 °C		
Electrical Load%	η_{el}	η_{hr}	Electrical Load%	η_{el}	η_{hr}
98%	0.236	0.632	92%	0.314	0.562
94%	0.244	0.649	84%	0.307	0.569
82%	0.227	0.682	75%	0.297	0.580
70%	0.22	0.705	67%	0.286	0.587
58%	0.217	0.765	50%	0.255	0.628

Table 4
Capacity factor of CHP/HP combined system at partial loads for CHP = 5 kW_{el}/HP = 16 kW_{th} and for CHP = 60 kW_{el}/HP = 250 kW_{th}.

Condensing micro CHP (Prototype)			Commercial CHP (Valmet)		
$C_{f,HP}$	$C_{f,CHP}$	C_{sys}	$C_{f,HP}$	$C_{f,CHP}$	C_{sys}
1	1	100.00%	1	1	100.00%
0.9	1	94.55%	0.9	1	93.22%
0.8	1	89.10%	0.8	1	86.43%
0.7	1	83.66%	0.7	1	79.65%
0.6	1	78.21%	0.6	1	72.87%
0.5	1	72.76%	0.5	1	66.09%
0.4	1	67.31%	0.4	1	59.30%
0.3	1	61.86%	0.3	1	52.52%
0	0.98	44.61%	0	0.92	29.60%
0	0.94	42.79%	0	0.84	27.03%
0	0.82	37.32%	0	0.75	24.13%

The main results related to the present energy analysis can be outlined as follows:

- three charts were elaborated to correlate directly the typical machines parameters with the overall efficiency for heating. Thus, based on these thoretical values several correction factors were defined and mapped on specific charts in order to take into account the machines size mismatch for their coupling and the energy source mix of national grid too. As regards this latter, an electrical efficiency threshold equal to 0.443 was identified to ensure the combined system actual profitability if compared with a single electric heat pump;
- the thermal power ratio between HP and CHP depends only on COP, size factor and CHP power to heat ratio;
- an analytical model to evaluate the combined system CHP/HP performance in off-design operating conditions was presented. In that case, the usefulness and validity of the previous maps were discussed;
- the size factor influence on the potential energy gains from the combined system use was discussed. From the analysis it emerged that the profitability for residential and industrial applications depends mainly on the price of electricity provided by the Grid to the cost of thermal energy provided by fuel ratio;
- a numerical simulation of two case studies was performed to evaluate the energy benefits coming from the use of the combined system by means of the elaborated method.

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