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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

Gianluigi Lo Basso [a], Benedetto Nastasi [b,*,1], Ferdinando Salata [a], Iacopo Golasi [a]

[a] Department of Astronautical, Electrical and Energy Engineering (DIAEE), Sapienza University of Rome, Via Eudossiana, 18, 0184 Rome, Italy
[b] Department of Architectural Engineering and Technology (AE+T), TU Delft University of Technology, Julianalaan 134, 2628BL Delft, The Netherlands

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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

* Corresponding author.
E-mail addresses: benedetto.nastasi@outlook.com, benedetto.nastasi@uniroma1.it (B. Nastasi).
[1] http://it.linkedin.com/in/benedettonastasi.

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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.