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Overall energy performance of polyvalent heat pump systems

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Buildings account for almost 40% of energy consumption in Italy, being one of the most energy-consuming and polluting sectors. The increasing electrification of HVAC systems requires an effort on the adoption of more efficient and sustainable technologies. The article aims to quantify the potential of polyvalent heat pumps, also in comparison to traditional heat pumps.

Keywords: polyvalent heat pumps, performance coefficients, gaussian load curves, partial load, energy savings, economic savings

The necessity to reduce primary energy consumption and greenhouse gases (GHG) emissions and to improve the energy efficiency of the power generation technologies is the objective of a wide range of policies within the energy sector in Europe [1]. Focusing on the building sector, due to the significant impact that HVAC systems have on the overall energy consumption of non-residential buildings (e.g. commercial, hospital, public administration ones, etc.), to achieve the European targets more efficient technologies should be used.

Traditional HVAC systems use different generation units to provide separately space cooling and space heating. For cooling, chillers are the most used technology; they produce chilled water in order to remove heat. On the other hand, boilers, heat pumps and district heating are used to produce hot water for space heating terminals. Reversible heat pumps, which can generate both hot or chilled water accordingly to the season, represent a more recent solution. However, it is not uncommon, due to building design and different use of the different spaces within the building, to have simultaneous requirements of heating and cooling in the same building. In this situation, both generation units should be used, and, in case of heat pumps, only one service can be provided at once.

In this framework, hybrid heat pumps, also called polyvalent heat pumps, represent a smart and low-energy solution to the conditioning needs in systems where the heating demand is combined simultaneously or independently with the cooling request. In fact, these technologies are able to recover the heat removed from the space that needs to be cooled and, instead of rejecting it to the external environment, they use this heat to produce hot water for heating purposes (space heating or domestic hot water production). Therefore, the potential of the polyvalent units is twofold: firstly, they can supply both heating and cooling at once; moreover, they can achieve such result using a single fuel.

Whereas such technologies are used for applications of power to heat using electricity as energy carrier, the combination of renewable generation systems on-site can give additional benefits, such as reduction in dependency from the energy grid and decarbonization of the local energy system.

The Polyvalent heat pump: operation modes and applications

Focusing on the polyvalent heat pump technology, it may be useful to briefly introduce its operation modes and its possible applications.

In this study, the considered polyvalent units are 4-pipes heat pumps equipped with a flexible heat recovery system that allows three operating modes: heating only, cooling only or both heating and cooling contemporary. Each unit consists of three heat exchangers:

- A main heat exchanger to produce hot water or chilled water;
- A secondary heat exchanger to produce hot water only;
- A condenser/evaporator for heat rejection or heat absorption, depending on the system operating mode.

In detail, the analysis was focused on the 4-pipes technology, aiming to demonstrate the benefits aroused from the use of the polyvalent unit, where automatic management of hot and chilled water supply is required independently or contemporary. For this reason, the AUTOMATIC mode is studied.

In this mode there are three possible operating configurations, as shown in **Figure 1**:

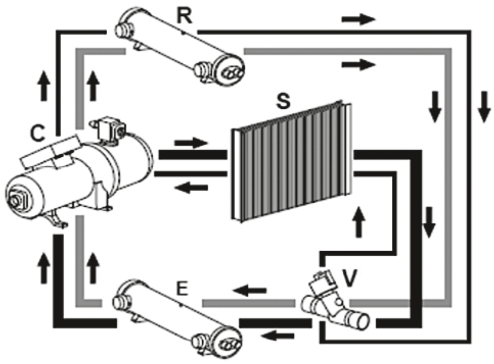
- AUTOMATIC 1 (A1): operation as air or water-cooled chiller (depending on the unit) only to produce chilled water at the main exchanger;
- AUTOMATIC 2 (A2): operation as air or water-cooled chiller (depending on the type) for the simultaneous production of chilled water at the main exchanger and hot water at the secondary exchanger;
- AUTOMATIC 3 (A3): operation as a traditional heat pump to produce hot water at the secondary exchanger.

The possibility to recover free energy and concretely use it represents the main difference between polyvalent and reversible heat pumps. Thus, hybrid units can find application in different sectors: residential buildings, hospital, offices, hotels, shopping centres. Both in the residential and in the tertiary sector (where complex surfaces and volumes characterize buildings), the simultaneous production of hot and chilled water may be required in some periods of the year, especially in the intermediate seasons (spring and autumn). This may occur due to large indoor thermal loads (e.g. electric equipment) in specific areas, to the different orientation of the building and/or to the different nature of occupants use of the indoor spaces. In all cases, the higher the heating and cooling loads required simultaneously, the greater the potentiality of the polyvalent heat pumps will be.

Methods

The aim of the study was to compare the performance of polyvalent heat pumps with respect to that of reversible heat pumps through the use of specific performance coefficients defined ad hoc. To do this, the methodology is divided into three steps:

1) Load curves and capacity curves modelling, in order to define the energy inputs of the model.
2) Creation of the algorithm for estimating the energy output
3) Definition of originally developed coefficients to make a comparison between performances of polyvalent and traditional heat pumps from an energetic and an economic standpoint.



▬ Only cold water production in the main exchanger (A1)

▬ Cold water production in the main exchanger and hot water production in the secondary exchanger (A2) (recovery unit).

— Only hot water production in the secondary exchanger (A3) (recovery unit).

Figure 1. Working principle of the polyvalent heat pump. V=expansion valve, E=evaporator (main heat exchanger), C=compressor, R=heat recover (secondary heat exchanger), S=condenser/evaporator [2].

Load and capacity curves modelling

The approach involved the use of theoretical and normalized Gaussian load curves. The choice of Gaussian shape is justified by the similarity to real load curves. Normalization was carried out with respect to the peak power, in terms of both heating and cooling.

As mentioned before, the potentiality of the polyvalent heat pump is higher when the contemporary demand of heating and cooling grows, where contemporaneity is intended as the simultaneous presence of both heating and cooling load in the *i-th* hour of the year. The percentage of contemporaneity was calculated as in **Equation (1)**:

$$\%cont = \frac{h_{cont}}{h_{year}} \qquad (1)$$

where h_{cont} represents the sum of the hours of contemporaneity during a year, and h_{year} are the 8 760 hours of the year.

Therefore, bundles of Gaussian pairs were created to evaluate different stages of contemporaneity, varying the standard deviation of the curve, by step of 50. In this way, 16 pairs of Gaussian curves were obtained, leading to a contemporaneity range from 13% up to 86%.

Figure 2 shows a pair of the obtained load curves, imposing a curtailment of values smaller than 10% of peak power, while in **Figure 3** the distribution of the different operating modes is shown.

In order to meet load demand, also capacity load curves were modelled. To strengthen the comparison between polyvalent and reversible heat pumps, similar characteristics were selected. Therefore, to explore different kinds of units, the analysis was carried out considering four diverse configurations, including: air condenser, four pipes, bi-circuits and different numbers of compressors, respectively 2,4 and 6 according to the chosen units. Additionally, the previous examples were analysed considering the use of an inverter for the two compressors unit. To each polyvalent unit corresponds a heat pump with the same characteristics, for a total of four pairs “polyvalent-reversible” heat pumps.

Starting from full load capacity data, from the producer datasheets, capacity curves were modelled, taking into account the two most influencing parameters for an air-condensing unit: the external air temperature and the operation at partial load.

First of all, weather data from the European software *Photovoltaic Geographical Information System* (PVGIS) for the city of Turin were used.

Then, since the full load capacity for the temperature defined by the European standard [3] are available, capacity curves in function of the air temperature were obtained by linear interpolation.

The combined effect of the influence of the external air temperature and the operation in partial load conditions was then investigated, using **Equations (2) & (3)**. Thanks to the datasheets, the part-load levels of the units and the relative quantities involved were known.

When using polyvalent heat pump, in A2 operating mode, the main condenser is by-passed, while the heat recovery heat exchanger is used. Therefore, the influence of temperature is worthless.

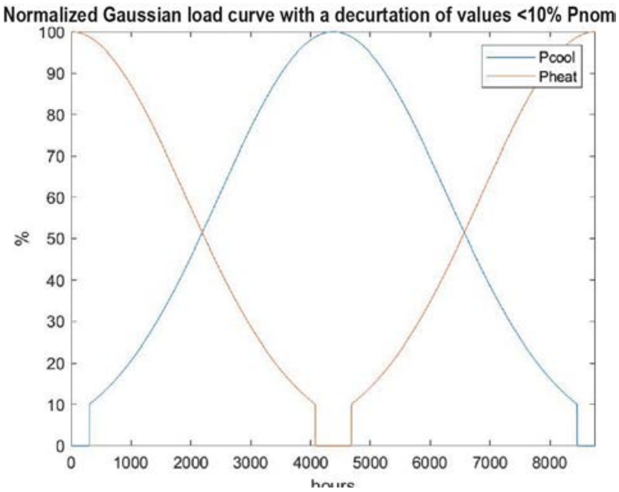


Figure 2. Example of Gaussian load curves.

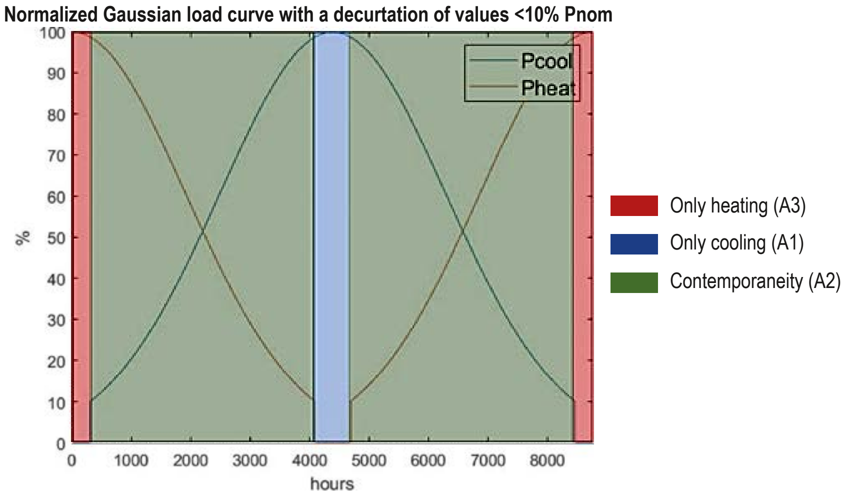


Figure 3. Operation mode during a year.

Algorithm

Once load and capacity curves were defined for each hour of the year, the algorithm for the calculation of the energy consumption and coefficients was implemented.

It is worth noting that, when reversible heat pump is considered, the algorithm is allowed to choose only between cooling only and heating only modes. For this machine, when contemporaneity occurs, it was assumed that heat pump is able to cover only the highest load, while the other one remains uncovered. On the other hand, polyvalent heat pump can shift between all the three operating modes.

For both polyvalent and reversible heat pumps, when the capacity of the unit is exceeded, demand is met using an electric boiler.

Overall performance evaluation

In order to show a global picture about the energy performance of the system on yearly basis, some additional coefficients are defined. The first coefficient here introduced considers the portion of non-served load of the two compared units and it is called *Non-Served Load Coefficient (NSLC).* The *NSLC* is defined by **Equations (4)–(6)**.

This coefficient allows to estimate the energy convenience of the polyvalent unit with respect to the traditional machine.

$$Capacity(Text, PL) = DC_{fl}(Text) * \frac{DC_{pl,i}}{DC_{nom}} \quad (2)$$

$$Pel(Text, PL) = Pel_{fl}(Text) * \frac{Pel_{pl,i}}{Pel_{nom}} \quad (3)$$

where

DC_{nom} = Nominal capacity at nominal conditions [kW];

$DC_{fl}\,(T_{ext})$ = Nominal capacity as a function of external air temperature (T_{ext}) [kW];

$DC_{pl.i}$ = Nominal capacity at the *i-th* partialisation degree of the unit [kW];

Pel_{norm} = Absorbed electrical power at nominal conditions [kW];

$Pel_{fl}\,(T_{ext})$ = Absorbed electrical power as a function of external air temperature (T_{ext}) [kW];

$Pel_{pl.i}$ = Absorbed electrical power at the *i-th* partialisation degree of the unit [kW].

A second coefficient is here introduced, named *Total Performance Coefficient (TPC)*, to give emphasis on the "cost" of production of the thermal energy (heating + cooling) in term of electricity needed and is defined by **Equation** (7).

At last, an economic coefficient, called *Fuel Expenditure Coefficient (FEC)*, was proposed, in order to compare the energy costs in both cases. It is inversely proportional to the *TPC* (**Equation (8)**).

For the economic evaluation, the price of electricity for non-domestic low voltage customers, with available power greater than 16.5 kW, was considered.

$$NSLC = \frac{Qns_{hp} - Qns_{poly}}{SE_{tot,hp}} \quad (4)$$

where

$$Qns_{hp} = Q_{elbu} + Q_{rem} \quad (5)$$

$$Qns_{poly} = Q_{elbu} \quad (6)$$

Qns_{hp} = load non-served by the traditional heat pump [kWh];

Qns_{poly} = load non-served by the polyvalent heat pump [kWh];

$SE_{tot,hp}$ = energy supplied by the heat pump [kWh];

Q_{elbu} = energy supplied by the electric backup [kWh];

Q_{rem} = load non-served due to contemporaneity (traditional heat pump cannot serve both loads) [kWh].

$$TPC = \frac{E_h + E_c}{E_{el}} \quad (7)$$

$$FEC = \frac{C_{el}}{E_h + E_c} \quad (8)$$

where

E_{el} = electric energy needed to meet the demand [kWh];

E_c = cooling energy supplied [kWh];

E_h = heating energy supplied, using polyvalent units this terms account also for the "free" recovered heat [kWh].

C_{el} = annual electricity cost [€], obtained from the product between annual electricity consumption and electricity price.

The value of 0.14 €/kWh was obtained as the average, for the year 2019, of the "*quota energia*" only (cost for energy, transport and management of the meter) defined by *Autorità di Regolazione per Energia Reti e Ambiente* (ARERA) [4], with IVA and excise duties not accounted.

Results and discussion

Simulations were run for all the four pairs of polyvalent and heat pumps. For the sake of brevity, only the results of the four compressors units are discussed. However, it is important to note that the trend of the coefficients is the same for all four pair of units considered.

NSLC

As reported in **Figure 4**, when contemporary demand of heating and cooling increases, the value of the first coefficient grows and it clearly appears how the capability of the polyvalent heat pump of generating simultaneously heating and cooling allows meeting a larger user's demand. For example, for a medium stage of contemporaneity of 52% (taken as reference value of contemporaneity hereinafter), the hybrid unit is able to meet almost 15% more demand with respect to the corresponding heat pump.

TPC

Figure 5 shows *TPC* for the reversible heat pump (HP) and the polyvalent heat pump (POLY), considering a 52% stage of contemporaneity. The blue bars represent the ratio between the cooling energy and the correspondent electricity consumed by the units, while the red bars represent the ratio between the heating energy and the correspondent electricity. *TPC* is then defined as the sum of the two contributions. As it can be seen in the figure, the red bar is much larger for the polyvalent heat pump, since the heat recovered in the hybrid machine is completely "free", not being produced by a fuel.

FEC

Figure 6 shows *FEC* for a 52% stage of contemporaneity. In this graph, the red bars represent the ratio between the cost associated to electricity consumed and the corresponding heating energy produced, while blue bars refers to cooling. The trend is specular to the *TPC*, being its direct consequence. Conversely to the previous situation, the red bar is lower for the polyvalent unit, since the recovered heat is not accounted as a fuel expenditure. When considering a 52% contemporaneity value, the economic saving associated to the use of the polyvalent heat pump is almost 32%. As expected,

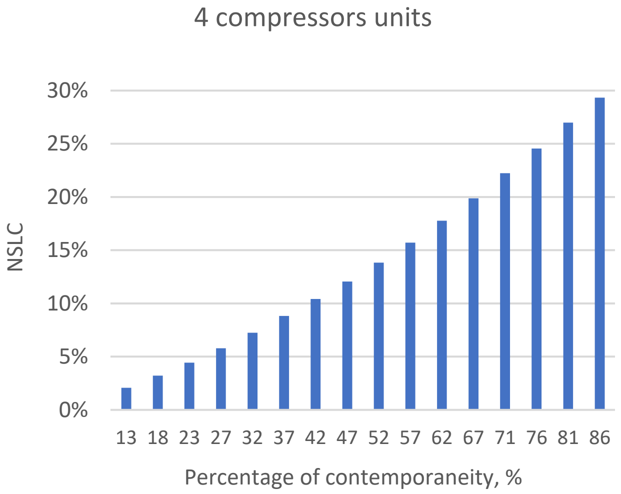


Figure 4. NSLC with respect to percentage of contemporaneity.

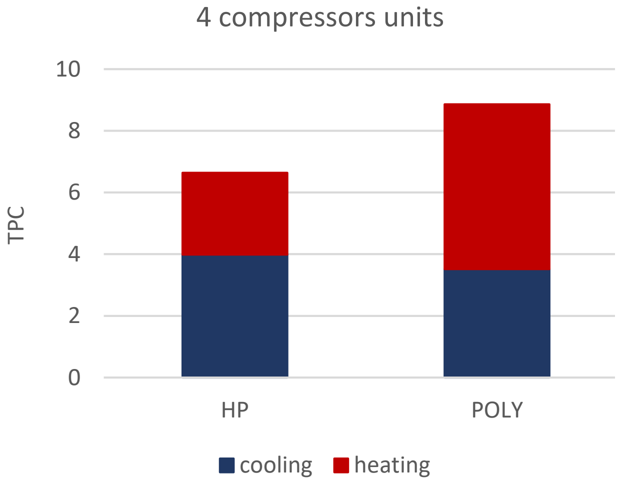


Figure 5. TPC for 52% of contemporaneity.

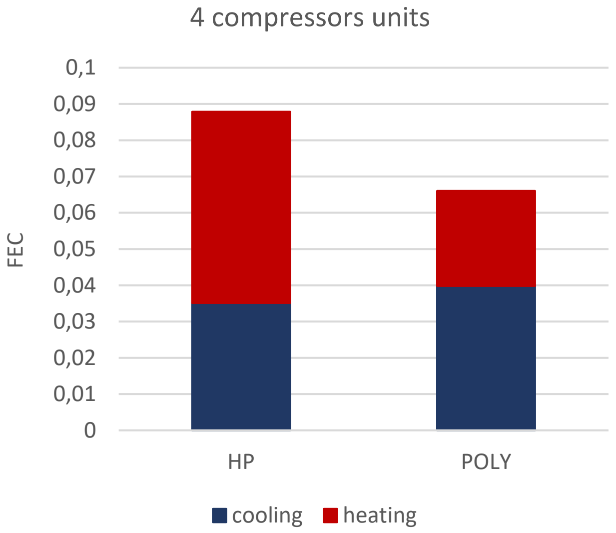


Figure 6. FEC for 52% of contemporaneity.

this value grows when the percentage of contemporaneity increases, reaching the maximum value of 73% of savings for the 86% of contemporaneity. Considering the medium range of contemporaneity (between 32% and 71%), the obtainable savings span from 13% to 55%.

Conclusions

The need for reducing the energy and environmental impact of HVAC systems is leading to the development and use of more sustainable technological solutions. Among them, polyvalent heat pumps can be cited, which main benefit with respect to existing technologies is the capability of meet contemporary heating and cooling demands, and thus representing an interesting technological solution for many applications. Thanks to the introduction of newly developed coefficients, the efficacy of polyvalent units with respect to traditional heat pump was highlighted. The capability of this innovative solution to exploit the potential free energy derived from the heat recovery can lead to significant savings in terms of energy consumption and fuel expenditure. As expected, convenience increases when the hours of simultaneous request for heating and cooling grow. To provide a complete analysis of the economic benefits of these units, cost-benefit analyses will be carried out in future works, allowing to encompass also other economical parameters, as investment and maintenance costs. ■

References

[1] European Commission, A Roadmap for moving to a competitive low carbon economy in 2050, 2011.

[2] RHOSS SpA proprietary technical documentation.

[3] UNI EN 14825 - Air conditioners, liquid chilling packages and heat pumps, with electrically driven compressors, for space heating and cooling - Testing and rating at part load conditions and calculation of seasonal performance.

[4] ARERA, electricity cost for 2019, https://www.arera.it.

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