Contemporary and unbalanced loads in buildings: *new performance indicators*

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Giving the promising benefits potentially offered by polyvalent heat pumps, either used alone or coupled with other HVAC systems, for meeting contemporary and unbalanced loads, the paper aims to define new performance indicators able to assess the potentialities of these HVAC configurations, surpassing the existing literature and standard gaps.

Keywords: Polyvalent heat pumps, Key Performance Indicators, contemporary and unbalanced heating and cooling loads, HVAC systems

Introduction

The polyvalent heat pump (PHP) is currently recognized as a promising HVAC technological solution for buildings, thanks to its capability to provide heating and cooling services simultaneously and independently, and not only seasonally (as traditional reversible heat pumps) [1, 2]. In particular, the use of PHPs, alone or in conjunction with other HVAC systems (e.g., chillers, heat pumps, etc.), can provide several benefits in terms of reduced fuel expenditure, environmental impacts, and costs [2]. However, despite the potentialities of PHPs, little literature is present regarding their modelling and valorisation; in this regard, there is a gap in literature on the possible metrics or key performance indicators (KPIs) to be used to value PHPs operations and benefits, also when compared with other widespread systems [2]. So far, indeed, PHPs performances have been evaluated in terms of the well-known seasonal indexes SCOP (Seasonal Coefficient of Performance) and SEER (Seasonal Energy Efficiency Ratio), compliant with the EN 14825 standard [3]. If these metrics are particularly useful to express the potentialities of traditional heat pumps (HPs), which provide one service at once (cooling or heating, exploiting a seasonal changeover), SEER and SCOP are not suitable enough for the PHPs performance assessment [2]. According to EN 14825, indeed, the seasonal indexes are computed using linear loads and defining the number of hours of heating and cooling seasons and the reference temperature bands for their calculations, according to diverse climatic conditions (i.e., warmer, average, and colder climates) [3]. Aiming to estimate the PHPs performances, some criticalities arise from this approach. It is limiting to consider fixed temperature ranges for the loads definition, as well as to define two separate and independent heating and cooling seasons; indeed, using this approach, it is not possible to account for possible contemporary heating and cooling requests, or to consider the number of contemporaneity hours, and these aspects are the main advantages of PHPs. In the light of the above, the work aims to develop new KPIs able to include the assessment of the hours of contemporary heating and cooling demands, to quantify and valorise the benefits that the use of PHPs can offer. Furthermore, thanks to the recent spreading of effective management and control systems, diverse technological solutions can be efficiently integrated to properly serve building loads. Especially in case of unbalanced heating and cooling loads over the year, it is interesting to consider the possibility of coupling more units with lower nominal capacities (among which also PHPs), rather than oversizing single units to meet the highest load. In support to this, there is the necessity to define proper annual indicators, able to include in a single metric all the specific performances of the units when working according to specific operation modes. Starting from an applicative study, the paper wants to discuss the potentialities arising from the coupling of PHPs with other systems thanks to efficient management and control systems able to strategically optimize the use of the two technologies in an effective way in case of unbalanced loads.

Method

The methodological approach is composed of two main parts: *i)* numerical experimentation, needed to model the coupling between load profiles and units operation dynamics; and *ii)* KPIs definition, aimed to define a set of metrics able to express the technical performances of the analyzed technological solutions [1, 2]. The numerical modelling phase is developed around three methodological steps, which allow to: *i)* create the load profiles; *ii)* define the units operation modes; and *iii)* model the load-unit coupling, considering partial loads and external air temperature as influencing parameters [1, 2]. In order to generalize the methodological framework and disengage it from specific case studies, cooling (P_C) and heating (P_H) load profiles are distributed along the hours of the year according to theoretical normalized Gaussian curves [1, 2, 4], assuming the possibility to have contemporary requests and fixing a specific percentage of contemporaneity. During non-contemporaneity hours, only cooling and heating loads are present, while contemporaneity hours are characterized by simultaneous heating and cooling requests. Thanks to the technical characteristics of the PHP, the unit works according to three main operation modes: A1 or cooling only (the PHP works as a traditional chiller); A3 or heating only (the PHP works as a traditional heat pump); and A2 or combined heating and cooling. In this latter mode, the PHP allows the recovery of heat from the evaporating process that otherwise would be wasted [1, 2, 4]. Knowing that for the PHP, only two modes can be activated in each hour, it is possible to identify five combinations of operation modes: $A1_{NCont}$ (cooling only load in non-contemporaneity hours), $A3_{NCont}$ (heating only load in non-contemporaneity hours), A2 (combined heating and cooling request), $A2+A1_{Cont}$ (when A2 mode requires an integration in A1 mode to meet the cooling demand during contemporaneity hours) and $A2+A3_{Cont}$ (when A2 mode requires an integration in A3 mode to meet the heating demand during contemporaneity hours). In the model, $P_C(i)$ and $P_H(i)$ loads were associated to the correspondent functioning modes for each hour. The performances of air-cooled units, of interest for this paper, are influenced by external air temperatures; moreover, also partial load condition reflects on the performances of heat pumps. Therefore, to consider both influencing parameters, an ad-hoc numerical model was developed to create the capacity curves of the units, based on real commercial units data from technical documentation [5] (i.e., heating and cooling capacities, absorbed electric powers, COPs, EERs) and to couple load and supply sides with an hourly time-step, considering the combined effect of partial load conditions and external air temperatures. More details on the numerical model can be found in [1, 2, 4].

Due to the current lack of appropriate KPIs for assessing the technical performances of PHPs, with a specific attention on contemporary operation modes, the model supports the definition of proper performance metrics. Specifically, in line with the existing performance coefficients for heat pumps [3], five indexes were developed to evaluate the performances in different operation modes. Each metric is calculated as the ratio between the total requested energies (E) and the relative absorbed electric energies (E_{el}) for a specific operation mode, as shown in eq. 1-5. The eventual integration of an electric back-up system (with a unitary efficiency) for heating peak demands is included into the

KPIs computation. Even though some of the metrics ($SCOPnc_{mode}$, $SCOPc_{mode}$, $SEERnc_{mode}$, $SEERc_{mode}$) can partly recall the standard-based and commercially diffused SCOP and SEER, it is important to note that there are differences in their definition.

$$SCOPnc_{mode} = \frac{E_{A3,NCont}}{E_{el,A3,NCont}} \quad (1)$$

$$SEERnc_{mode} = \frac{E_{A1,NCont}}{E_{el,A1,NCont}} \quad (2)$$

$$S\text{-}EXP_{mode} = \frac{E_{A2}}{E_{el,A2}} \quad (3)$$

$$SCOPc_{mod} = \frac{E_{A3,Cont}}{E_{el,A3,Cont}} \quad (4)$$

$$SEERc_{mod} = \frac{E_{A1,Cont}}{E_{el,A1,Cont}} \quad (5)$$

Furthermore, to define a single annual indicator able to express the whole annual performances of the considered units, including possible multi-unit configurations, the Annual Performance Indicator (API) was developed. API is calculated as the sum of the five previously mentioned KPIs, each weighted on the operation hours of the unit in each operation mode. In detail, by defining w_1, w_2, w_3, w_4, and w_5 as the fractions of annual hours in which the PHP operates in $A3_{NCont}$, $A1_{NCont}$, A2, $A3_{Cont}$ and $A1_{Cont}$, respectively, the API metric is computed as expressed in eq. 6 below:

A summary of the five developed KPIs, with the indication of the hourly weighting coefficients used for the API calculation, is provided in **Figure 1**.

Application

The developed methodological approach was tested for comparing two air-cooled HVAC configurations to satisfy the same load curves. In line with the current air conditioning trends, according to which cooling requests are surpassing heating ones (because of the recent increment of external air temperatures [6]), unbalanced loads were considered; specifically, maximum heating and cooling loads were set equal to 350 kW and 630 kW, respectively.

As shown in **Figure 2**, load profiles were built based on Gaussian-shaped profiles, considering an average percentage of contemporaneity, equal to 52% [1, 2, 4]. All calculations are developed considering the climate of Strasbourg (i.e., "average" climate, according to [3]).

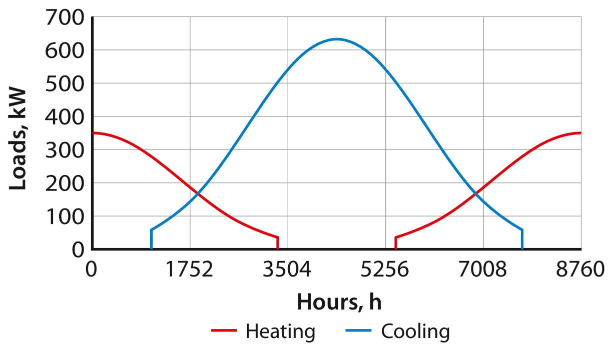

Figure 2. Gaussian-shaped unbalanced load profiles: 52% percentage of contemporaneity.

$$API = w_1 \cdot SCOPnc_{mode} + w_2 \cdot SEERnc_{mode} + w_3 \cdot S\text{-}EXP_{mode} + w_4 \cdot SCOPc_{mode} + w_5 \cdot SEERc_{mode} \quad (6)$$

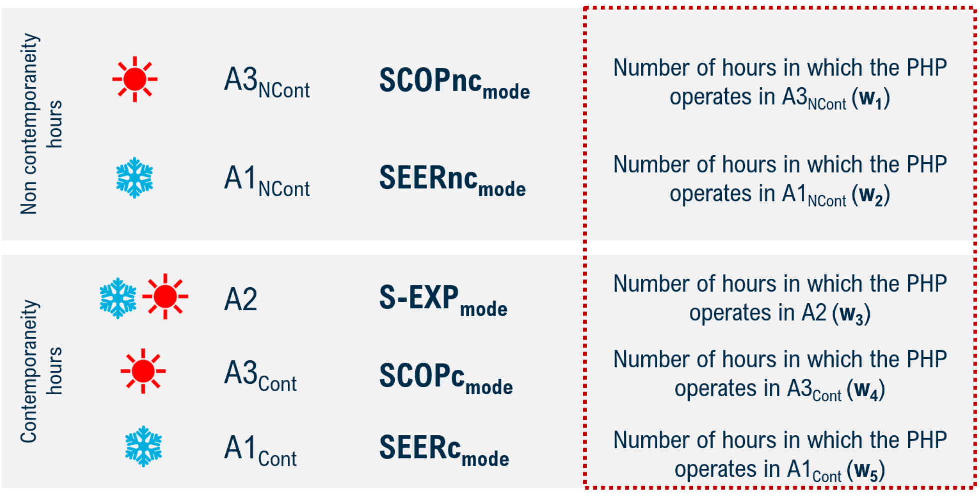

Figure 1. Definition of performance metrics for each operation mode and identification of hourly weighting coefficients.

Two 4-pipes HVAC configurations were considered and compared in terms of the defined KPIs:

1. A single polyvalent heat pump (660 kW, 6 scroll compressors) sized to meet the cooling request. This configuration considers the use of a single unit to satisfy all loads.
2. A polyvalent heat pump (370 kW, 4 scroll compressors) sized to meet the heating request, coupled with a chiller (330 kW, 4 scroll compressors), the latter used as integration unit to match the remaining cooling load. In this case, being the PHP alone not able to satisfy all loads, an efficient multi-technology management system is required to combine the integrated solutions and to define and apply their start-up and operation strategies in an efficient way.

Results and discussion

The two configurations were compared in terms of the defined KPIs, using the same numerical model. Based on the load distribution among the considered operation modes, both configurations are characterized by the same weighting coefficients, depending only on the load curves, and not on the considered units. Specifically, w_1 and w_2 are equal to 24%, while the remaining percentage (i.e., 52%, percentage of contemporaneity) is distributed among the other coefficients (28%, 5% and 19% for w_3, w_4 and w_5 respectively).

It is worth mentioning that, if the PHP works in all operation modes in both configurations, the chiller of the multi-unit configuration works only in $A1_{NCont}$ and $A1_{Cont}$, to integrate the PHP in meeting the cooling loads. To compute the API index for the multi-unit configuration, therefore, there is the need to couple the performances of the two units in both $A1_{NCont}$ and $A1_{Cont}$ in a single coefficient. As a result, $SEERnc_{mode,SYSTEM}$ and $SEERc_{mode,SYSTEM}$ were defined, calculated as the ratio between the cooling requests served by both units and the total electricity consumption of both units, in $A1_{NCont}$ and $A1_{Cont}$ respectively. For the multi-unit configuration, thus, the API formula is updated as in eq. 7, where the chiller contribution is included only in the new-defined indicators, while, for this application, $SCOPnc_{mode}$, $SCOPc_{mode}$ and $S\text{-}EXP_{mode}$ are characteristic of the sole PHP (pls. see eq below):

Table 1 summarizes the results obtained for the two compared HVAC configurations in terms of the five developed metrics. Based on its definition, $S\text{-}EXP_{mode}$ values for both configurations are higher than other metrics, since the A2-related index considers the capability of the unit to provide a double service with a single electricity consumption. Values are comparable between the two configurations; it is worth mentioning that the results are strongly dependent on the partial load conditions of the considered units.

Table 1. *KPIs results for the two compared configurations.*

Configuration 1: PHP		Configuration 2: PHP +chiller	
$SCOPnc_{mode}$	3.0	$SCOPnc_{mode}$	3.0
$SEERnc_{mode}$	4.5	$SEERnc_{mode,SYSTEM}$	5.0
$S\text{-}EXP_{mode}$	8.0	$S\text{-}EXP_{mode}$	8.5
$SCOPc_{mode}$	2.5	$SCOPc_{mode}$	3.0
$SEERc_{mode}$	4.5	$SEERnc_{mode,SYSTEM}$	5.0

The presented application allowed to assess the higher technical convenience of the multi-unit configuration, compared to the use of the sole PHP. Indeed, the API of the PHP+CHILLER configuration (approximately 5.5) results higher than the other solution (approximately 5), and thus can be used as a metric to numerically express how it would be more beneficial to use two units with a lower nominal capacity for matching the considered unbalanced loads, rather than using a single unit with a higher nominal capacity. It is worth mentioning that the obtained results are related to the fixed boundary conditions of the specific application presented in this work. However, the methodological approach can be extended to other profiles, characterized by diverse contemporaneity levels and peak loads; starting from the development of diverse profiles, the multi-unit configuration can achieve higher benefits in terms of the API metric, and its deviation with respect to the PHP alone can increase up to 15-20%.

The considered systems were compared also in environmental and financial terms. Investment costs were computed considering real units costs, while energy costs were calculated considering 2019 Italian electricity prices (only variable quota considered) [7].

$$API = w_1 \cdot SCOPnc_{mode} + w_2 \cdot SEERnc_{mode,SYSTEM} + w_3 \cdot S\text{-}EXP_{mode} + w_4 \cdot SCOPc_{mode} + w_5 \cdot SEERc_{mode,SYSTEM} \quad (7)$$

As reported in **Table 2**, indeed, the multi-unit configuration appears to be more attractive, thanks to its lower investment and energy costs, as well as its lower environmental impact, in terms of generated CO_2 emissions (electricity emission factor was taken from [8]).

Conclusions

Polyvalent heat pumps are becoming important actors of the transition of the building sector, thanks to the several benefits arising from their capability of providing heating and cooling services simultaneously and independently. However, still few methodological approaches and metrics are present to express the potentialities of this technology, used alone or in combination with other units, thanks to the use of proper management and control systems. The work aimed to develop new metrics to assess the performances of HVAC systems (both single- or multi-unit) in presence of contemporary and unbalanced heating and cooling loads in buildings. Based on these newly developed KPIs, and mainly on API, the work allowed the comparison of two configurations (PHP vs. PHP+CHILLER). The integration of PHP and chiller, using units with lower nominal capacities, has appeared to be more beneficial in technical terms (i.e., API), as well as from financial and environmental standpoints, with respect to the sole PHP with higher capacity. Future works will be developed to refine the numerical approach, to test the defined KPIs with other HVAC configurations and diverse contemporary load profiles, as well as to enlarge the set of metrics, always aiming to valorize the technologies capabilities of meeting contemporary loads. ■

Table 2. *Environmental and financial outcomes for the two compared configurations.*

	Configuration 1: PHP	Configuration 2: PHP +chiller
Investment cost [€]	88,027	87,172
Energy cost [€/y]	143,393	141,267
CO_2 emissions [t/y]	337.5	332.5

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