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Research paper

Innovative metrics to evaluate HVAC systems performances for meeting contemporary loads in buildings

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ABSTRACT

The significant impacts of the building sector ask for an urgent transition, which will be profoundly shaped by the HVAC sector. Due to recent energy demands modification, strongly associated to climate change consequences, buildings are asked to be equipped with HVAC systems capable of satisfying in a cost-effective way even contemporary space heating and cooling demands; in this context, the polyvalent heat pump (PHP) is recognized as a promising solution, being able to serve both requests simultaneously and independently, differently from the more widespread reversible heat pumps. However, despite the potentialities that the PHP could offer, still few efforts have been reserved to it in literature and existing metrics have proven not to be able to evaluate the capabilities of HVAC systems in meeting contemporary loads. Therefore, to fill this gap, through the development of a proper numerical model to investigate and simulate diverse systems operations on a common basis, the paper aims to develop new indicators able to include the assessment of the contemporaneity of request. To this purpose, the research: (i) proposes innovative technical indicators able to value PHPs performances, with particular attention to the assessment of the hours with contemporary space heating and cooling demands; and (ii) compares PHPs with other all-electric HVAC configurations using ad-hoc metrics, extending the discussion to other relevant domains, covering financial and environmental spheres. Thanks to the applicative study, the paper demonstrates the efficacy of the proposed indicators to evaluate the performances of HVAC systems for meeting contemporary loads in buildings, succeeding in valuing the technologies able to provide simultaneous heating and cooling services using a single unit. In addition, results highlight that PHPs can be considered a good trade-off from a multi-domain standpoint, emphasizing how this technology can be useful to drive the transition towards the electrification of thermal uses.

1. Introduction

The desired energy transition puts the building sector in the spotlight, due to its significant energy and environmental impacts. The sector contributes to 10% of global direct CO_2 emissions, value that increases up to approximately 30% if indirect CO_2 emissions from electricity and heat sectors are accounted (IEA, 2019). The sector transition appears extremely challenging, but urgent, due to the existing pressure for improving energy efficiency to sustainably meet an ever-increasing demand, especially for cooling needs; these considerations put the HVAC sector in the crosshairs. Given the significant impacts that HVAC systems have on the overall consumption of a building (Martinopoulos et al., 2018; Li et al., 2020; Gonzáles-Torres et al., 2022), there is the necessity to adopt increasingly more efficient and sustainable technologies, to decrease energy consumptions and emissions, without affecting indoor air quality and occupants' thermal comfort (Li et al., 2020). To this purpose, in recent years, the European air conditioning market is pushing towards the exploitation of electric solutions, well recognizing the role of heat pumps (HPs) in the energy changeover. HPs are considered a mature technology, characterized by high energy efficiency, allowing to deliver "a thermal output several times greater than the required electric input" (Thomaßen et al., 2021), and thus guaranteeing significant energy and emissions reductions and long-term operational savings (Singh Gaur et al., 2021).

Furthermore, the transition of the HVAC sector needs to face the possible energy demand changes due to new occupants' habits and behaviours (i.e., the diffusion of smart working activities because of the COVID-19 pandemic), as well as to climate change effects (Tootkaboni et al., 2021). The modification of energy demand profiles opens the way to new energy systems considerations, increasingly asking them to easily satisfy in a cost-effective way even simultaneous space heating and cooling demands (Abbà et al., 2020b; Crespi et al., 2021). In this context,

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Nomenclature

α	Fraction of non-contemporaneity hours with heating only request in a year
β	Fraction of non-contemporaneity hours with cooling only request in a year
γ	Fraction of contemporaneity hours in a year (i.e., percentage of contemporaneity)
γ_1	Fraction of contemporaneity hours in a year when PHP works in HC mode only
γ_2	Fraction of contemporaneity hours in a year when PHP works in HC mode and requests a heating only integration
γ_3	Fraction of contemporaneity hours in a year when PHP works in HC mode and requests a cooling only integration
ACI	Aggregate Contemporaneity Indicator
API	Annual Performance Indicator
AWI	Annual Weighted Index
c	Contemporary
C_e	Energy cost [€/y]
C_g	Global cost [€]
C_i	Investment cost [€]
CO	Cooling only
CO_2	Carbon dioxide
COP	Coefficient of Performance
CPI	Cooling Performance Indicator
DC	Declared capacity [kW]
E	Energy demand [kWh/y]
E_{el}	Electric energy consumed [kWh/y]
EER	Energy Efficiency Ratio
GHG	Greenhouse gas
HC	Contemporary heating and cooling
HCPI	Contemporary Heating & Cooling Performance Indicator
H_{cont}	Hours of contemporaneity of request of heating and cooling during a year
H_{year}	Total hours in a year
HO	Heating only
HP	Heat pump
HPI	Heating Performance Indicator
HVAC	Heating, ventilation, and air conditioning
i	i-th hour of the year
j	j-th HVAC configuration
k	k-th partial load step
KPI	Key Performance Indicator
nc	Non-contemporary
nom	Nominal conditions
P	Unit capacity in function of air temperature and partial load conditions
PHP	Polyvalent heat pump
PL	Partial load
SCOP	Seasonal Coefficient of Performance
SEER	Seasonal Energy Efficiency Ratio
T_{ext}	External air temperature

attention is devoted to the polyvalent heat pump (PHP) solution, which is considered a promising, even still not widespread technology; if compared with traditional reversible heat pumps, the PHP novelty is the capability to provide space heating and cooling independently and simultaneously, not only seasonally, using a single unit (Crespi et al., 2021). The PHP installation can be particularly beneficial in non-residential buildings (e.g., hotel, residences, glass-fronted offices, etc.) (Byrne and Ghoubali, 2019), where it may be possible to experience cooling and heating requests at the same time or in a limited time span (Janes et al., 2017). According to Vio et al. (2017), the use of a PHP in place of traditional technologies could halve energy consumptions, allowing significant benefits in terms of reduction of primary energy consumptions and greenhouse gases (GHG) emissions, as well as of life cycle and operating costs. Despite the acknowledged potentialities of the PHP solution, still little literature exists regarding the modelling of its operation dynamics and the valorization of its benefits, through metrics able to evaluate its potentialities in case of contemporary requests.

The quantification and evaluation of the performances of buildings and HVAC systems is essential for driving the transition of the sector and must be supported by the definition and use of appropriate Key Performance Indicators (KPIs). Li et al. (2020) proposed a classification of indicators according to three levels: (i) whole-building; (ii) energy system; and (iii) component or equipment level, assuming a component as an individual equipment or appliance installed within a building (e.g., lighting system, boiler, chiller, etc.) and a system as the "aggregation of individual equipment and components that delivers a particular building service". Even though whole-building-level KPIs are widely diffused, they may be not appropriate enough for assessing the performance of HVAC solutions in a more detailed way, thus asking for more informed KPIs at system- or component-level. Specifically, if component-scale KPIs are more diffused and mature, being mostly used to estimate the performance of an equipment, also in line with standards and labels, system-level metrics are less deployed, even though their use can be beneficial, allowing the assessment of the overall performance of multi-unit systems, rather than that of a single component (Li et al., 2020).

Focusing on the HVAC sector, and specifically on the heat pump market, it is worth mentioning that most of the KPIs traditionally used for the technological assessment are component-based. To cite some, the performance metrics COP (Coefficient of Performance) or EER (Energy Efficiency Ratio), which are typically used to assess the heating and cooling performances of heat pumps and chillers, can be defined as component-level indicators. Similar considerations are valid for SCOP (Seasonal Coefficient of Performance) and SEER (Seasonal Energy Efficiency Ratio), introduced by standards and commercially used to evaluate the seasonal operations of these machines (EN14825, 2016). So far, SEER and SCOP indices have been used also to express PHPs performances. However, if these approaches and metrics are suitable for HPs and are diffused and comprehensible both at commercial and private (investor/consumer) scales, their use is not appropriately targeted to PHPs. Firstly, the standard-based methods deployed for SEER and SCOP computation do not assume the possibility of having contemporary requests. Therefore, these metrics are not able to capture and estimate in quantitative terms the capability to fulfil contemporary heating and cooling needs, which is the main characteristic of the PHP technology, asking for new component-level KPIs capable of including the assessment of contemporary services provision. Moreover, if PHPs can intrinsically satisfy contemporary demands with a single unit, traditional HVAC systems require the combination of more units to meet the same loads, moving the lens from a component-based (i.e., single unit) to a system assessment, analysing the combination of more units. Furthermore, when comparing diverse technological solutions for buildings, attention is mainly devoted to technical-related metrics, capable of quantifying only the energy performances of the analysed HVAC systems (Li et al., 2020). However, to increase the awareness on the multiple benefits of the compared technological solutions, multi-domain KPIs are needed, touching also financial and environmental spheres to surpass a merely technical-based approach. The introduction of non-technical KPIs allows to target not only commercial or industrial professionals, more accustomed to use energy metrics, but also private and public stakeholders (e.g., investors, consumers, policy makers, etc.), who may be more sensible to financial or environmental aspects (Bompard et al., 2020; Crespi and Bompard, 2020).

In the light of the above, attempting to fill the existing literature and standard gaps, the paper comes out from the necessity to define a common and homogeneous basis for the comparison between PHPs and other traditional HVAC systems. The paper presents a numerical method to model and simulate the operation dynamics of PHPs and other HVAC configurations, using theoretical load profiles that admit the presence of contemporary space heating and cooling needs on an annual basis, aiming to propose innovative metrics to evaluate the performances of HVAC systems in presence of contemporaneity of requests. With this goal in mind, given the potentialities of the PHPs, proper component-level KPIs to value their benefits in terms of technical performance are developed, to overcome the limits of the traditional market-diffused indices. Then, to compare PHPs performances with those of other multi-unit all-electric HVAC configurations, a set of multi-domain KPIs is defined, extending the analysis also to environmental and financial spheres.

The paper is structured as follows; Section 2 is dedicated to a brief description of the PHP dynamics, while in Section 3 the developed methodological framework is depicted, providing insights on the modelling framework and on the identification of relevant KPIs. The characteristics of the HVAC configurations studied are reported in Section 4 together with the definition of the relevant assumptions and boundary conditions for the study. Finally, Section 5 summarizes the main results achieved, while Section 6 draws the main conclusions and identifies possible future trajectories of the research.

2. Overview of polyvalent heat pumps

The polyvalent heat pump represents a "smart" HVAC solution for buildings characterized by simultaneous space heating and cooling demands (Crespi et al., 2021). The unit, which can be described as a heat pump equipped with a heat recovery system, is compatible with different configurations of air conditioning plants and could be applied in either 2- or 4-pipes systems. This paper focuses on air-cooled units and on 4-pipes systems, using an automatic management of the water supply.

A typical PHP is equipped with three heat exchangers (Janes et al., 2017): (i) the main heat exchanger, used to produce either hot or chilled water; (ii) the secondary heat exchanger (or heat recovery system), used to produce only hot water; and (iii) the evaporator/condenser, used for heat absorption or rejection, depending on the operation mode. As shown in Fig. 1, the PHP can operate in three different modes, activating per each operation mode only two exchangers; according to the user's requirements, it can shift its operation mode in every moment. The red line identifies the "heating only (HO)" operation mode, according to which the PHP operates as a traditional heat pump, providing hot water to the secondary heat exchanger (working as a condenser); in this mode, the refrigerant fluid moves between the secondary heat exchanger (R) and the evaporator (S). The blue line, instead, identifies the "cooling only (CO)" operation mode, according to which the unit works as a traditional chiller,

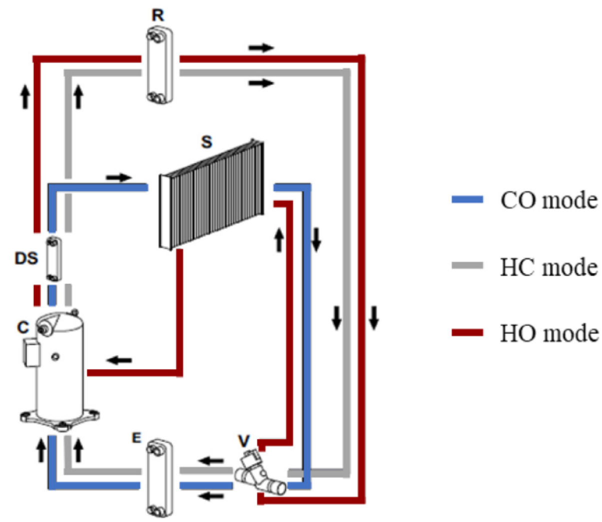

Fig. 1. PHP working principle. S = evaporator/condenser; C = compressor; E = main heat exchanger; R = secondary heat exchanger (recovery unit); V = lamination valve; DS = desuperheater (auxiliary).

producing chilled water at the main heat exchanger (E), using S as condenser. In both HO and CO modes, the air-cooled unit is directly in contact with the external heat source (i.e., air), through the evaporator/condenser S. The main novelty offered by the PHP, however, is the "contemporary heating and cooling (HC)" mode (represented with the grey line in Fig. 1), which is active only in case both services are simultaneously requested by the user. In this case, the chilled and hot water are produced at the main and secondary heat exchanger, respectively, by-passing the evaporator/condenser (S), and, thus, removing the direct contact with the external air (i.e., the unit behaves as a water-to-water heat pump) (Abbà et al., 2020a,b; Crespi et al., 2021). In this mode, the unit can recover the heat removed from the evaporation, which otherwise would be wasted, representing a free quota of thermal energy that does not require any additional fuel to be generated.

3. Methodological approach

This section summarizes the methodological approach developed with the final scope of proposing innovative metrics for capturing the performances of HVAC configurations in meeting contemporary loads in buildings, with a focus on PHPs. A global scheme of the methodological steps followed in the analysis is provided in Fig. 2. Specifically, Section 3.1 is devoted to the description of the numerical model used to build and match heating and cooling demand curves with the units operation modes (steps 1, 2 and 3 of the scheme); Section 3.2, instead, is dedicated to the definition of relevant component- and system-level KPIs, developed to either value PHP characteristics or to compare its benefits with respect to other HVAC system configurations (steps 4 and 5 of the methodological approach).

3.1. Numerical experimentation

As depicted in Fig. 2, the numerical modelling is divided into three main steps: (1) creation of load profiles; (2) definition of units operation modes; and (3) modelling of load-unit coupling.

Starting from the first step, to generalize the methodological proposal and to disengage it from specific case study applications, a new theoretical model was proposed, in which space heating and cooling load profiles are distributed along the hours of the year according to theoretical Gaussian-shaped curves, to

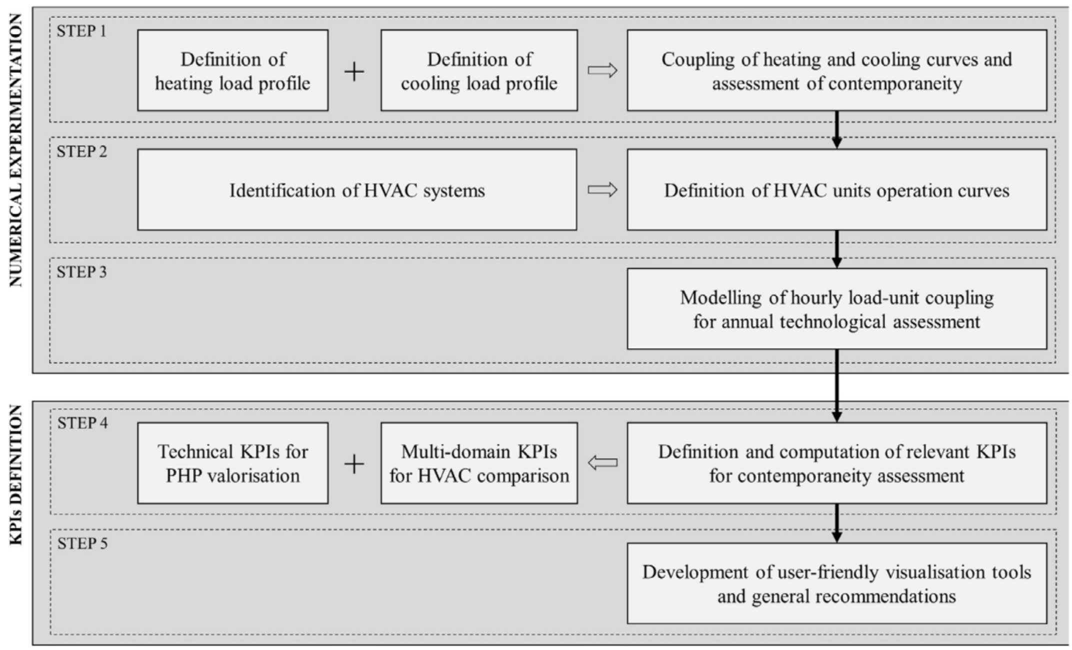

Fig. 2. Scheme of the methodological approach.

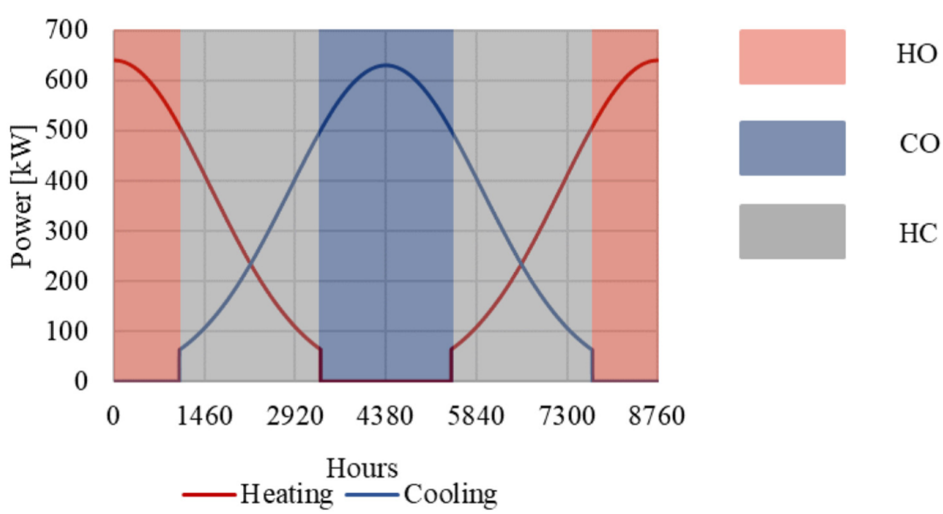

Fig. 3. Distribution of contemporary and non-contemporary requests according to the Gaussian-shaped space heating and cooling profiles.

obtain typical non-real profiles, based on which different HVAC systems can be tested and compared (Abbà et al., 2020a,b; Crespi et al., 2021). Fig. 3 shows an example of the distribution of the contemporary and non-contemporary space heating and cooling requests, with the coloured zones representing the HO (red), CO (blue) and HC (grey) operation modes previously described; specifically, the HO and CO zones are characterized by a single request (either space heating or cooling), while the grey areas identify all hours in which both space heating and cooling requests are greater than 0.

The Gaussian-shaped load curves were created to highlight the influence of the time variable on the units performances. The coupling of heating and cooling profiles allows to evaluate the total number of hours with contemporaneity of requests, where contemporaneity is intended as the simultaneous request of both heating and cooling in the i-th hour of the year. The contemporaneity of the load profiles can be varied for modelling purposes by modifying the standard deviation of the curves (i.e., enlarging/narrowing the curves, to increase/reduce the hours with double service). As expressed in Eq. (1), based on the distribution of the space heating and cooling profiles, it is possible to estimate the percentage of contemporaneity (γ).

$$\gamma = \frac{H_{cont}}{H_{year}} \tag{1}$$

where H_{cont} represents the sum of the hours of contemporaneity of request of heating and cooling during a year, while H_{year} are the 8760 hours of the year.

According to the coupling of space heating and cooling profiles, the demands can be divided among the operation modes of the units (i.e., HO, CO, and HC, if present), by hourly associating heating and cooling requests to a specific mode. Depending on whether the mode is activated or not in the hours of contemporaneity, it is distinguished in HOc (COc) or HOnc (COnc), to differentiate the operating conditions. For PHPs, all five modes are

Table 1
Operation modes combination for HPs and PHPs.

	Heat pump	Polyvalent heat pump
Non-contemporaneity hours	HOnc or COnc	HOnc or COnc
Contemporaneity hours	HOc or COc	HC or HC + HOc or HC + COc

allowed, while reversible HPs cannot work in HC. In detail, it is important to specify that reversible HPs are able to meet only one of the two contemporary requests (either HOc or COc); therefore, to satisfy both contemporary space heating and cooling loads of Fig. 3, there is the need to combine more units in parallel. Table 1 resumes the operation modes combinations for HPs and PHPs. Specifically, for PHPs, in HC mode, the portion of heat recovered from the system is limited to be 30% higher than the refrigeration capacity; thus, in case, during H_{cont}, the HC mode is not enough to match the requested space heating and cooling loads, HOc or COc modes are activated as integration (the developed model allows two PHP operation modes to be active each hour, if needed).

The second step of the methodological approach consists in the definition of the units operation curves, according to their main influencing parameters, based on real commercial units data. Indeed, to simulate the operation dynamics of the considered technologies, it is fundamental to account for the dependency of their performances on two variables: external air temperature (for air-cooled units) and partial load conditions (Abbà et al., 2020a,b; Crespi et al., 2021). Focusing on the external air temperature dependency, declared capacities, absorbed powers and coefficients of performances (COP or EER) were gathered for four representative temperatures (defined by the standard EN 14825) according to the service (−7, 2, 7, 12 °C for heating; 20, 25, 30, 35 °C for cooling). Considering a linear relation between unit capacities and external air temperatures, a linear interpolation for the intermediate temperature values was used. As for the dependency on partial loads conditions, units data were extracted from technical documentation, for 10 steps from 10% to 100% of the nominal power.

Finally, once defined the hourly load profiles and the operation modes characteristics, the model allows to combine the effects of the influencing parameters on the final capacity of the units and to couple the Gaussian loads with the operation conditions of the HVAC systems (Abbà et al., 2020a,b; Crespi et al., 2021).

For HOc, HOnc, COc, COnc modes, per each i-th hourly timestep, the numerical model first identifies the unit declared capacity as a function of the sole external air temperature ($DC(T_{ext})(i)$) and of the k-th partial load condition ($DC_{PL(k)}\,(i)$), depending on the operation mode. To combine both dependencies, the final capacity of the unit $P\,(T_{ext}, PL)\,(i)$ is calculated per each hour as in Eq. (2).

$$P\,(T_{ext}, PL)\,(i) = DC(T_{ext})(i) \cdot \frac{DC_{PL(k)}(i)}{DC_{nom}} \tag{2}$$

where DC_{nom} represents the full load capacity at nominal conditions [kW], while T_{ext} and PL indicate external air temperature and partial load, respectively. Following the same assumptions, it is possible to estimate the hourly absorbed electric power values.

When considering the HC mode, the condenser/evaporator is by-passed and substituted by the heat recovery (see Fig. 1); therefore, in this operation mode, only partial load conditions influence the PHPs performances, since there is no more direct contact with the air heat source. In this case, the final capacity corresponds to the unit declared capacity dependent on the sole partial load conditions $DC_{PL(k)}(i)$, as in Eq. (3).

$$P\,(PL)\,(i) = DC_{PL(k)}(i) \tag{3}$$

For all HVAC systems, including PHPs, when the capacity of the unit is exceeded, the remaining demand is met using an auxiliary electric boiler.

3.2. Definition of relevant KPIs

The numerical model allowed to create a common background for the comparison of different HVAC systems, enabling the step of definition and computation of appropriate component- and system-level KPIs, to evaluate the systems performances in presence of contemporary loads.

3.2.1. Component-level KPIs for PHPs valorization

Firstly, attention is devoted to the definition of proper metrics capable of capturing PHPs potentialities, not fully valued by existing indicators. To account for the units capability of meeting heating and cooling loads simultaneously and independently, five component-level KPIs were defined, each representative of the performances of PHPs in the different operation modes, as reported in Table 2. All indices are calculated as the ratio between the annual heating and/or cooling energy requests (E) when the unit works in a specific mode and the associated annual electricity consumption (E_{el}). The integration of an electric back-up system, when needed, is included in the KPIs computation.

During non-contemporaneity hours, HPInc and CPInc indices are calculated, depending on the energy request. Even though these metrics can recall the standard-based and commercially used SCOP and SEER indicators, it is important to consider that there are some differences in their definition, considering both the construction of the load curves and the temporal allocation of the energy needs (Crespi et al., 2021). In detail, the load curves proposed by EN14825 (2016) are linear-shaped, divided depending on the season and directly dependent on external air temperatures, the latter being limited between the design temperature (dependent on the climate) and 16 °C for the heating season and between 16 °C and 40 °C for the cooling one. Moreover, the standard foresees the identification of the frequency of occurrence of the temperatures (and consequently of the heating and cooling requests), associating a number of hours to each temperature bin, according to the selected climate. Conversely, the developed numerical approach considers Gaussian-shaped profiles to approximate load curves, distributed throughout the whole year, and thus not being directly related to the external temperature; moreover, no temperature limits are fixed for heating and cooling requests. Both assumptions allow to admit the presence of contemporary loads to be met, which represent a key aspect for PHPs.

Concerning contemporaneity hours, three indices were defined. Specifically, the HCPIc metric was developed to isolate the PHPs performances when providing simultaneous heating and cooling energy in the HC mode. Moreover, in case during contemporaneity hours, the HC mode is not able to fully match the requested heating and cooling loads, an integration in HOc or COc modes is needed; in these hours, HPIc and CPIc metrics were defined (their definition is similar to HPInc and CPInc metrics).

Starting from the above, a new annual aggregate KPI was developed, able to integrate all the PHPs performances during contemporaneity and non-contemporaneity hours. The metric, named Annual Performance Indicator (API), is computed as the sum of the five component-level KPIs, each weighted on the relative operation hours in the specific modes, as shown in Eq. (4).

$$API = \alpha \cdot HPI_{nc} + \beta \cdot CPI_{nc} + \gamma_1 \cdot HCPI_c + \gamma_2 \cdot HPI_c + \gamma_3 \cdot CPI_c \tag{4}$$

where α indicates the fraction of non-contemporaneity hours with heating only request in a year, β the fraction of non-contemporaneity hours with cooling only request, γ_1 the fraction of contemporaneity hours in which the PHP works in HC mode alone, and γ_2 and γ_3 the fractions of contemporaneity hours in which the PHP, that is working in HC mode, requests an integration in HOc and COc mode, respectively (the sum of γ_1, γ_2 and γ_3, equal to γ, is the percentage of contemporaneity hours in a year).

Table 2
Definition of component-level KPIs for PHPs.

Operation mode	KPI	Equation	Temporal resolution
HOnc	Non-contemporary Heating Performance Indicator (*HPInc*)	$HPI_{nc} = \frac{E_{HOnc}}{E_{el,HOnc}}$	Non-contemporaneity hours with heating only request
COnc	Non-contemporary Cooling Performance Indicator (*CPInc*)	$CPI_{nc} = \frac{E_{COnc}}{E_{el,COnc}}$	Non-contemporaneity hours with cooling only request
HOc	Contemporary Heating Performance Indicator (*HPIc*)	$HPI_{c} = \frac{E_{HOc}}{E_{el,HOc}}$	Contemporaneity hours with heating only integration
COc	Contemporary Cooling Performance Indicator (*CPIc*)	$CPI_{c} = \frac{E_{COc}}{E_{el,COc}}$	Contemporaneity hours with cooling only integration
HC	Contemporary Heating & Cooling Performance Indicator (*HCPIc*)	$HCPI_{c} = \frac{E_{HC}}{E_{el,HC}}$	Contemporaneity hours with heating and cooling simultaneous request

Table 3
Definition of multi-domain component- and system-level KPIs for HVAC configurations. COM = component; SYS = system.

Domain	KPI	Typology		Temporal resolution
		PHP	Other HVAC systems	
Technical	Non-contemporary Heating Performance Indicator (*HPInc*)	COM	COM	Non-contemporaneity hours with heating only request
	Non-contemporary Cooling Performance Indicator (*CPInc*)	COM	COM	Non-contemporaneity hours with cooling only request
	Aggregate Contemporaneity Indicator (*ACI*)	COM	SYS	Contemporaneity hours
	Annual Weighted Index (*AWI*)	COM	SYS	Year
Environmental	Annual CO_2 emissions	COM	SYS	Year
Financial	Percentage variation of investment cost w.r.t PHP ($\Delta C_i\%$)	–	SYS	–
	Percentage variation of energy cost w.r.t PHP ($\Delta C_e\%$)	–	SYS	Year
	Percentage variation of global cost w.r.t PHP ($\Delta C_g\%$)	–	SYS	Configurations lifetime

3.2.2. Component- and system-level KPIs for PHPs comparison with other HVAC configurations

To compare the PHPs performances with those of other multi-unit HVAC configurations in terms of capability of service provision, when meeting the same loads, a set of multi-domain component- and system-level KPIs was defined. The considered configurations are always composed of a reversible heat pump, able to match both heating and cooling requests in non-contemporaneity hours; during H_{cont}, the primary HP is forced to work either in HOc or COc mode, requiring an integration system (e.g., chiller, electric boiler, reversible heat pump) to meet the non-served contemporary load.

The different metrics are summarized in Table 3, divided by domain, and showing their main characteristics in terms of typology (component- or system-level) and temporal resolution (Crespi et al., 2021).

Starting from the technical KPIs, three metrics were considered, aiming to reflect and capture all the operation modes of the compared HVAC systems during the year. In detail, the previously defined HPInc and CPInc metrics were extended also for the multi-unit configurations. Both indicators are identified as component-level KPIs, since they assess the heating or cooling performances of a single machine (i.e., PHP or primary reversible heat pump) during non-contemporaneity hours.

Furthermore, to analyse the units behaviour during contemporaneity hours, an aggregate KPI was defined, named Aggregate Contemporaneity Indicator(ACI), calculated as in Eq. (5).

$$ACI = \frac{E_{HC} + E_{HOc} + E_{COc}}{E_{el,HC} + E_{el,HOc} + E_{el,COc}} \tag{5}$$

As shown in Table 3, ACI can be considered either a component-level or a system-level KPI, depending on the HVAC configuration under investigation. More precisely, if for the PHP the metric is a component-level KPI, since the PHP can satisfy contemporary cooling and heating needs with a single unit, for the other HVAC configurations, more units are parallelly requested to meet them; for these systems, therefore, ACI is identified as a system-level KPI, since it considers the combination of more individual components for its computation.

Moreover, to integrate all the previous metrics for obtaining an annual assessment, the Annual Weighted Index (AWI) was developed, summing HPInc, CPInc and ACI metrics, each weighted using proper coefficients. Two indicators were defined; the AWI_{hourly} (Eq. (6)) was obtained calculating specific coefficients based on the operation hours of each metric, while the AWI_{equal} (Eq. (7)) was calculated using equal weights.

$$AWI_{hourly} = \alpha \cdot HPI_{nc} + \beta \cdot CPI_{nc} + \gamma \cdot ACI \tag{6}$$

$$AWI_{equal} = \frac{100}{3} \cdot HPI_{nc} + \frac{100}{3} \cdot CPI_{nc} + \frac{100}{3} \cdot ACI \tag{7}$$

where γ indicates the fraction of contemporaneity hours in a year (i.e., percentage of contemporaneity). As for ACI, also AWI can be either a component-level or a system-level KPI, depending on the considered configuration.

Furthermore, the analysis was extended to other domains to include potential conflicting perspectives within the technological assessment. In detail, from the environmental standpoint, annual carbon dioxide (CO_2) emissions were computed, starting from the electricity consumptions.

In financial terms, the configurations were compared in terms of investment and annual energy costs. Both indicators are reported in percentage terms, expressing them as variations of the cost voices of the different HVAC configurations with respect to the PHP (as reported in Eqs. (8) and (9)).

$$\Delta C_i\%(j) = \frac{C_{i_{PHP}} - C_{i_j}}{C_{i_j}} \tag{8}$$

$$\Delta C_e\%(j) = \frac{C_{e_{PHP}} - C_{e_j}}{C_{e_j}} \tag{9}$$

where $C_{i_{PHP}}$ and $C_{e_{PHP}}$ represent the investment and the energy cost of the PHP, while C_{i_j} and C_{e_j} represent the investment and the energy cost of each j-th multi-unit configuration.

Finally, to combine these financial KPIs, the global cost was considered, blending all the expenses borne to consumers over the entire configuration lifetime, allowing a more complete comparison between the diverse technological solutions. As introduced in the 2010 Energy Performance of Building Directive (EPBD) Recast (European Parliament, 2010), its calculation accounts for the initial investment cost of the HVAC configurations and for the annual expenses (e.g., maintenance, energy costs), the latter discounted at the present value (EN15459-1, 2017). In line with $\Delta C_i\%$ and $\Delta C_e\%$ metrics, the considered KPI evaluates the percentage deviation of the global cost between PHPs and the other configurations, as reported in Eq. (10).

$$\Delta C_g\%(j) = \frac{C_{g_{PHP}} - C_{g_j}}{C_{g_j}} \tag{10}$$

where $C_{g_{PHP}}$ and C_{g_j} represent the global cost of the PHP and of the j-th multi-unit system, respectively.

All financial indicators are calculated for the multi-unit systems compared to the PHPs, thus representing system-level KPIs; moreover, focusing on the temporal resolution of the computation, if the energy cost is calculated on an annual basis, the global cost is calculated for the entire lifetime of the configurations.

4. Application

The proposed methodological approach was tested for four HVAC configurations, all compared using the same load curves, having set the maximum value of heating and cooling needs to 640 kW and 630 kW, respectively (Crespi et al., 2021), as shown in Fig. 3.

In line with the electrification roadmap foreseen for the building sector transition (IEA, 2019), only all-electric configurations were accounted. As shown in Table 4, Conf. 1, 2 and 3 are multi-unit systems and have in common the deployment of a reversible heat pump, which is assumed to fully cover the non-contemporary loads (both heating and cooling), while requiring an integration during contemporaneity hours. The type of integration system is what distinguishes one system from the others; specifically, for Conf. 1 an electric boiler is used as integration for matching contemporary heating, while in Conf. 2 a chiller is used for contemporary cooling; Conf. 3, instead, integrates two reversible HPs during contemporaneity hours, with the primary reversible HP working by priority, satisfying the highest load (either heating or cooling, depending on the loads distribution) per each hour, while the smaller HP is used to cover the remaining loads. In this configuration, both systems can shift their operation modes (only between HOc and COc) during H_{cont}; to manage this operation dynamics, an ad-hoc control system should be implemented for allowing the HPs hourly switch.

Technical data of PHP, HPs, and chiller, concerning nominal capacities, partial load values and efficiencies were collected from commercial datasheets; for the electric boiler, a unitary efficiency is assumed. Then, fixed boundary conditions were set, in relation to the main influencing factors: the external air temperature and the percentage of the contemporary requests. In detail, the "average" climate (i.e., Strasbourg) according to EN 14825 was selected (EN14825, 2016) and hourly mean air temperature values were extrapolated from the European software Photovoltaic Geographical Information System (PVGIS), developed by the Joint Research Center (JRC); an average value of 52% for the percentage of contemporaneity was considered.

Finally, for KPIs computation, a CO_2 emission factor of 0.42 $kgCO_2$/kWh for electricity was considered (ISO52000-1, 2017). Italian electricity prices were derived from ARERA (2019) for the year 2019 (only variable quota was considered), considering the price for non-domestic users, with an installed power higher than 16.5 kW. Real investment costs of commercial units were considered, with the sole exception of the electric boiler, which cost was derived from Witkowski et al. (2020). Finally, for the global cost calculation, a 4% real interest rate and a 20 years lifetime was considered for all solutions, while annual maintenance costs were computed as percentages of the units investment costs, according to EN15459-1 (2017).

5. Results and discussion

This section presents the main outcomes coming from the calculation of the metrics previously described. From the numerical experimentation model, energy demands were extrapolated. These values are not dependent on the type of configuration considered, which in turn influences only the distribution of the operation modes between the units during contemporaneity hours and the annual electricity consumptions.

5.1. Component-level KPIs: evaluation of PHP performances

Focusing on the sole PHP, Table 5 presents the outcomes of the developed component-level KPIs.

The results suggest that the proposed HCPIc metric succeeds in capturing the real potentiality of the PHP to provide two contemporary services in the same hour. Indeed, HCPIc reaches the highest value, since, when operating in HC mode, the heating capacity represents a free quota of thermal energy. Looking at the other KPIs, cooling services are globally delivered with higher efficiencies, in line with traditional reversible heat pumps. When comparing heating performances in contemporaneity and non-contemporaneity hours, the discrepancies between the corresponding indicators are imputable to different air temperatures and partial load conditions, which highly affect the KPIs computation; the same is true for CPInc and CPIc.

Each indicator in Table 5 can be associated to a portion of hours of the year during which the unit works according to the specific operation mode. To evaluate the overall performance of the PHP during the whole year, the API indicator was computed, weighting the metrics of Table 5 using the coefficients presented in Fig. 4.

As previously cited, α and β indicate the fractions of non-contemporaneity hours in which the PHP works in HOnc and COnc modes, respectively; the two weights are balanced and both equal to 24% (according to the Gaussian-shaped load profiles). The remaining fraction (the grey one in Fig. 4) represents the total percentage of contemporaneity (i.e., 52%) and can be subdivided into γ_1, γ_2 and γ_3 weights, depending on the PHP operations. The aggregation of the KPIs into an annual metric led to an API equal to 5.12. According to the weights distribution, the API numerical value is lower than the HCPIc, but higher than the other non-annual indexes, since γ_1 is the fraction with more percentage relevance.

Table 4
HVAC configurations.

	Non-contemporary cooling	Non-contemporary heating	Contemporary cooling	Contemporary heating
Conf. 1	Primary HP 660 kW	Primary HP 660 kW	Primary HP 660 kW	Electric boiler 508 kW
Conf. 2	Primary HP 660 kW	Primary HP 660 kW	Chiller 520 kW	Primary HP 660 kW
Conf. 3	Primary HP 660 kW	Primary HP 660 kW	Primary HP (660 kW) or Secondary HP (370 kW) (depending on priorities)	
Conf. 4	PHP 660 kW	PHP 660 kW	PHP 660 kW	PHP 660 kW

Table 5
Component-level KPIs for PHP.

HPInc	CPInc	HPIc	CPIc	HCPIc
2.84	4.70	3.08	4.70	8.24

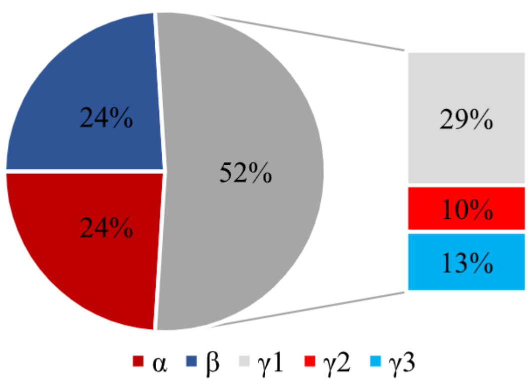

Fig. 4. Weights distribution for API calculation.

Table 6
Results of technical KPIs for the four HVAC configurations.

	Conf. 1	Conf. 2	Conf. 3	Conf. 4
HPInc	2.92	2.92	2.92	2.84
CPInc	4.79	4.79	4.79	4.70
ACI	1.64	3.91	3.95	5.41

5.2. System-level KPIs: comparison of different HVAC configurations

After a focus on PHP features and performances, the work compared it with other multi-unit all-electric HVAC configurations, following the same numerical model and under the same boundary conditions (i.e., heating and cooling loads, average climate and percentage of contemporaneity).

5.2.1. Technical KPIs

To compare the four selected HVAC configurations, the analysis moves from five to three technical KPIs (i.e., HPInc, CPInc and ACI), which are summarized in Table 6.

Since the demands to satisfy are the same and Conf. 1, 2 and 3 use the same unit (i.e., primary reversible HP) to cover the non-contemporary loads, HPInc and CPInc for these configurations are identical and equal to 2.92 and 4.79, respectively. Conf. 4 presents lower HPInc and CPInc values, being characterized by slightly lower performance coefficients in these modes (with respect to the reversible HP), privileging the efficiency during contemporaneity hours.

Moreover, ACI was developed to assess the overall behaviour of the analysed configurations in presence of contemporary needs; the higher the ACI, the higher the overall efficiency of the energy delivered during contemporaneity hours is. Looking at Table 6, as expected, it emerges that Conf. 1, composed by the primary HP coupled with the electric boiler, is characterized by the worst contemporaneity performance (ACI = 1.64), since the boiler (exploited as secondary unit to meet contemporary heating) has a lower efficiency with respect to the other units. Conversely, the proposed metric confirms that the PHP is the best performing system in contemporaneity hours, since, thanks to the heat recovery system, the heating service is provided without any electricity expenses. The remaining configurations are characterized by intermediate ACI results, with a slightly better performance for Conf. 3, which ideally optimizes the operation of the involved units (primary and secondary reversible HPs), working by priority during contemporaneity hours.

Finally, to consider the overall performance of the studied configurations, two annual indicators AWI_{hourly} and AWI_{equal} were developed. The outcomes of the AWI_{hourly} computation are summarized in Fig. 5. Its trend reflects the one observed for ACI; indeed, since all the configurations present comparable HPInc and CPInc values, the annual efficiency is particularly sensitive to the performance during contemporaneity hours (which represent 52% of the total), thus advantaging Conf. 4 over the others. Comparing the worst and the best performing systems (i.e., Conf. 1 and 4, respectively), the AWI_{hourly} value increases by around 71%.

Moreover, to better evaluate the effect of using weights proportional to service provision hours in the AWI calculation, an additional annual indicator (AWI_{equal}) was computed, using equal weights for the three indices. Fig. 5 shows the comparison between the two aggregated indicators, highlighting how the AWI_{hourly}, which assigns more relevance to the ACI indicator, is the one that better valorizes the configurations with higher contemporaneity efficiencies (i.e., PHP). Conversely, the adoption of equal weights for the computation of the AWI_{equal} advantages solutions with low contemporaneity efficiency (i.e., Conf. 1), attributing equal importance to all KPIs; for the configuration considering the coupling of the primary HP with the electric boiler, AWI_{hourly} results lower than AWI_{equal}. Concerning Conf. 2 and 3, HPI, CPI and ACI indicators are quite balanced, and therefore the difference between the two annual KPIs is small. Therefore, the results show the efficacy of the AWI_{hourly} in valorizing the capabilities of the technologies in providing two simultaneous services at once, giving the right weight to the units efficiency in contemporaneity hours.

5.2.2. Multi-domain KPIs

This sub-section extends the discussion to other relevant domains, to include other perspectives into the technological assessment, presenting the outcomes of the considered financial and environmental KPIs. Starting from the financial evaluation, Fig. 6 presents the results in terms of $\Delta C_i\%$ (light blue), $\Delta C_e\%$ (light brown) and $\Delta C_g\%$ (salmon pink) metrics. By definition, a positive value means that the cost (i.e., investment, energy, or global cost) of the j-th multi-unit system is lower than that of the PHP.

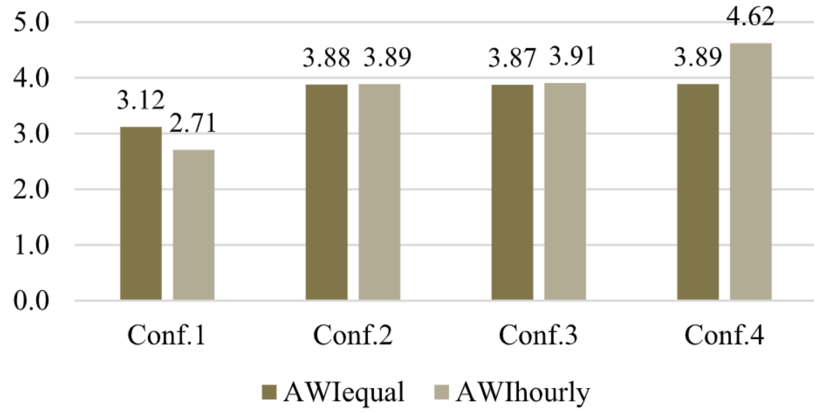

Fig. 5. Annual weighted indicators for the four HVAC configurations.

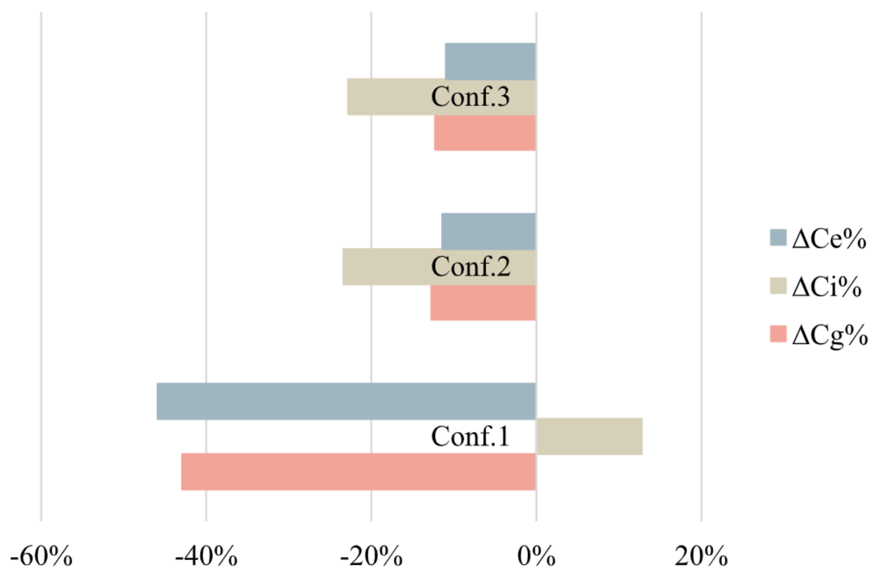

Fig. 6. Comparison of financial KPIs for the multi-unit HVAC configurations with respect to PHP.

Focusing on $\Delta C_i\%$, it is interesting to note that the only positive value is obtained for Conf. 1. This is because the electric boiler, despite its low efficiency, has an investment cost significantly lower than the other solutions. Conversely, since Conf. 2 and 3 are both composed by two units with still high upfront costs (HP + chiller, HP + HP), they are characterized by higher investment costs; both configurations present an investment cost more than 20% higher than the PHP. Considering $\Delta C_e\%$, all deltas are negative, meaning that the PHP is more convenient from the operational (energy) standpoint. In this case, differently from the previous one, the most disadvantageous system is Conf. 1, being the one characterized by the highest electricity consumption, which is in turn reflected into a higher energy expenditure. On the contrary, Conf. 2 and 3 involve the use of energy efficient technologies, resulting in lower electricity consumptions and related energy costs; both configurations present a $\Delta C_e\%$ of almost -11%. To couple this information into a single metric, the configurations were compared also in terms of global cost. When moving the analysis from a yearly to a life-cycle approach, the global cost reflects the expenses over the entire lifetime of the technological solutions, thus giving more importance to annual expenses, rather than to the initial investment cost. For this reason, for all configuration $\Delta C_g\%$ values are closer to $\Delta C_e\%$ since the energy cost is the most impacting contribution on a whole lifetime basis.

Moving to the environmental sphere, as expected, the annual CO_2 emissions reflect the energy consumptions of the compared configurations; specifically, the most impacting system is Conf. 1 causing 875 t/y, almost double the PHPs emissions (473 t/y).

Finally, for visualization purposes, the bubble plot presented in Fig. 7 is built, to compare the systems from a multi-dimensional standpoint. In detail, the graph gives a snapshot of the relative positioning of the configurations according to the three dimensions (technical, financial, and environmental), each represented using a proper KPI. Specifically, x- and y-axes represent the CO_2 emissions and the investment cost of each configuration, respectively, while the size of the bubbles varies as a function of AWI_{hourly}. According to the KPIs, the best solutions are those located in the bottom-left of the graph, having low emissions and investment costs. Moreover, to better reflect the characteristics of the energy demand, systems are positively judged when characterized by high AWI_{hourly} values (corresponding to larger bubbles). Conversely, the worst performing technologies can be found in the top-right of the graph and with a small size bubble, meaning high carbon footprint, high investment cost and low annual performance efficiencies.

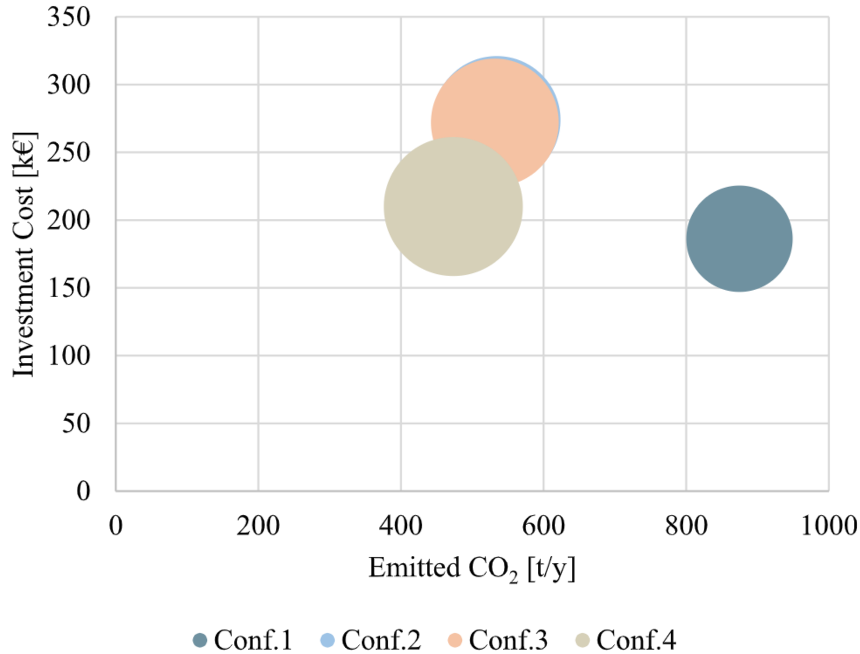

Fig. 7. Multi-perspective bubble graph (the size of the bubbles represents the value of the AWI_{hourly} index of each configuration).

Conf. 1, despite the lowest investment cost, which can make this solution attractive for private investors, presents a bad environmental and energy performance. Due to the high electricity consumptions, this configuration is the highest CO_2 emitter; moreover, as mentioned before, its performance in contemporaneity hours is worse compared to the other configurations, thus resulting in the lowest AWI_{hourly} among the compared solutions. Conf. 2 and 3 are characterized by relatively high AWI_{hourly} values and lower CO_2 emissions with respect to Conf. 1; however, they present the highest investment costs. Therefore, despite their good environmental and technical performances, these solutions are less attractive for the investors. Finally, Conf. 4 reaches at the same time the highest annual efficiency and the lowest environmental impact, while having a quite low investment cost, representing the best compromise between the different standpoints.

6. Conclusions

The transition of the building sector needs to be shaped by the deployment of increasingly efficient and low-carbon HVAC systems and a key role will be played by electric solutions, among which heat pumps. In this context, the polyvalent heat pump represents a promising technology, offering the possibility of providing space heating and cooling independently and simultaneously, and not only seasonally, as traditional reversible heat pumps. Despite its potentialities and benefits in terms of energy consumptions and costs reduction, still little literature is present on its modelling and valorization through the definition of proper metrics. Specifically, the performances of PHPs are currently assessed using existing and standard-based indicators (i.e., SEER, SCOP), which are no longer appropriate for this unit, not being able to consider and evaluate the occurrence of contemporary space heating and cooling requests in the same hour. In line with the above, through the development of an ad-hoc numerical model and using theoretical Gaussian-shaped load profiles, the paper aimed to propose innovative metrics to evaluate the performances of HVAC configurations in meeting contemporary needs. In detail, the work has defined proper component- and system-level KPIs to (i) value PHPs benefits and (ii) to compare their performances with those of other three multi-unit HVAC configurations, to estimate their efficiency of heating and cooling services provision, from a multi-domain perspective. More precisely, the PHP was compared with other more traditional all-electric solutions (mainly reversible heat pumps), which request the use of integrative units (e.g., heat pump, chiller, electric boiler) to match both demands during contemporaneity hours. Focusing on the sole PHPs, the work developed specific metrics to estimate their performances in each operation mode. Moreover, attention was devoted to the proposal of innovative metrics able to value diverse units behaviours during contemporaneity hours (i.e., Aggregate Contemporaneity Indicator, ACI) and on annual basis (i.e., Annual Weighted Index (AWI)). Both energy-related metrics allowed to compare diverse HVAC configurations on a common basis, showing the higher PHP performances with respect to other solutions, thanks to its capability of meeting contemporary space heating and cooling requests using a single unit. The application has shown the efficacy of the developed metrics in valuing PHPs potentialities compared with other multi-unit configurations, as demonstrated by the AWI_{hourly} result for the PHP, which reached a value more than 70% greater than that of the Conf. 1 (i.e., combination of a reversible HP with an electric boiler). Furthermore, besides technical indicators, the paper compared the diverse HVAC configurations also in environmental and financial terms, highlighting how the use of PHP in place of other more traditional configurations may be beneficial in both environmental (46% reduction of CO_2 emissions with respect to Conf. 1) and financial terms (46% and 43% reduction of energy and global costs, respectively, compared to Conf. 1). Thanks to the obtained results, it was possible to stress the importance of performing a technological assessment, not limiting the attention to technical or energy aspects, but extending the perspective to other relevant domains, more comprehensible also by a non-expert audience.

The work, still on-going, opens the way to further analysis. Even though the paper focused on PHPs, the comparison with other HVAC solutions have demonstrated the replicability of the methodology and the efficacy of the proposed indicators. Therefore, future work will be devoted to the extension to other technological solutions, including non-electricity-fuelled options (e.g., condensing gas boiler, biomass boiler) to cover the heating needs, due to the prominent share they still cover in the sector. Moreover, the model built based on Gaussian-shaped ideal profiles will be tested using real load profiles, coming from monitoring campaigns or from energy simulations, to investigate the validity of the model also in case of real demand characteristics (mainly non-residential), analysing the PHPs potentialities to match the loads of these building categories. Finally, new KPIs could be included into the methodological proposal, extending the set of component- and system-level metrics to be used for technological comparison and assessment.

CRediT authorship contribution statement

G. Crespi: Conceptualization, Investigation, Methodology, Software, Writing – original draft, Writing – review & editing, Visualization. **I. Abbà:** Conceptualization, Investigation, Methodology, Software, Writing – original draft, Writing – review & editing, Visualization. **S.P. Corgnati:** Conceptualization, Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data that has been used is confidential.

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