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Climate influence on seasonal performances of air-to-water heat pumps for heating

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Abstract

A mathematical model for the evaluation of the seasonal performances of electric air-to-water heat pumps for heating is used to analyze the efficiency of on-off heat pumps, multi-compressor heat pumps and heat pumps with inverter compressor, integrated by electric heaters as back-up system, in the service of several buildings located in different Italian climates.

The paper points out the importance of a good dimensioning of the heat pump as a function of the building energy signature and of the climate of the city where the building is placed, in order to enhance the system seasonal efficiency.

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Keywords: air-to-water heat pumps; SCOP; seasonal performances; bin-method; bivalent temperature

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1. Introduction

Nowadays the reduction of buildings energy needs is strongly required by the European Commission and heat pumps can help to achieve European targets because aero-thermal, geothermal and hydrothermal energy is recognized as renewable energy.

Air-to-water heat pumps are particularly suitable for the replacement of heat generators in energy retrofit of buildings, as air source is wherever available and they are easy to install and relatively cheap. Nevertheless, the performances of air-to-water heat pumps are strongly dependent on the external air temperature, which continuously changes in time during the heating season. As a consequence, the good sizing of the heat pump, which is crucial in order to obtain good seasonal performances, takes into account not only the building loads, but also the climate of

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the location where the building is located and the kind of control system of the device, which is responsible of the heat pump performances at partial loads. In fact, heat pumps work at nominal conditions only for a limited part of the heating season and authors like Bettanini et al. [1] and Henderson et al. [2] demonstrated as heat pumps seasonal performances are strongly influenced by the values assumed by the Coefficient Of Performance (*COP*) at partial loads.

In order to take into account the variability of the outside climate, the evaluation of air-source heat pumps seasonal efficiency (*SCOP*) is usually carried out through the bin-method. Many researchers have proposed calculation methods for the evaluation of heat pumps seasonal performances [3-7] and very recently [8] a simple mathematical model for the determination of the *SCOP* of building heating systems based on electric air-to-water heat pumps integrated by electric heaters as back-up systems is presented by taking into account different kinds of electric heat pumps, like mono-compressor, multi-compressor and inverter-driven heat pumps. The model presented in [8] utilizes the bin-method and it is derived from the European standard EN 14825 [9] and the Italian standard UNI/TS 11300-4 [10].

In this paper the model described in [8] is used to investigate the influence of the outside climate on the seasonal performances of different kinds of heat pumps coupled with different buildings. The results obtained point out the importance of the adoption of appropriate sizing rules for the heat pump in relation to the thermal characteristics of the building, the climate profile of the location, and the kind of heat pump regulation system.

2. Bin-method

For the evaluation of the heat pumps seasonal performances the European standard EN 14825 and the Italian standard UNI/TS 11300-4 suggest to model the outdoor climate by means of the bin-method. A bin represents the number of hours in which the external air temperature has a value within a fixed interval centered on an integer value of temperature and 1 K wide.

The standard EN 14825 splits Europe in three winter climates (Colder, Average and Warmer) and directly provides the bin trends for the heating season of each climate. The standard UNI/TS 11300-4, on the contrary, presents a calculation method, based on a normal external air temperature distribution, which allows to evaluate the bin profile of a specific location in Italy. The input data for this method are the local monthly average outdoor air temperature, outdoor design temperature (T_{des}) and monthly average daily solar radiation on horizontal plane (data available for Italy from the standards UNI 10349 [11] and UNI EN 12831 [12]).

The bin-method defined by the UNI/TS 11300-4 is here used to determine the bin distribution for the heating season of three different Italian cities: Brescia (45.32°N, 10.12°E), Florence (43.41°N, 11.15°E) and Trapani (38.01°N, 12.32°E). The conventional heating season is from October 15th to April 15th for Brescia, from November 1st to April 15th for Florence and from December 1st to March 31st for Trapani. The bin profiles obtained for these three Italian cities are shown in Fig. 1.

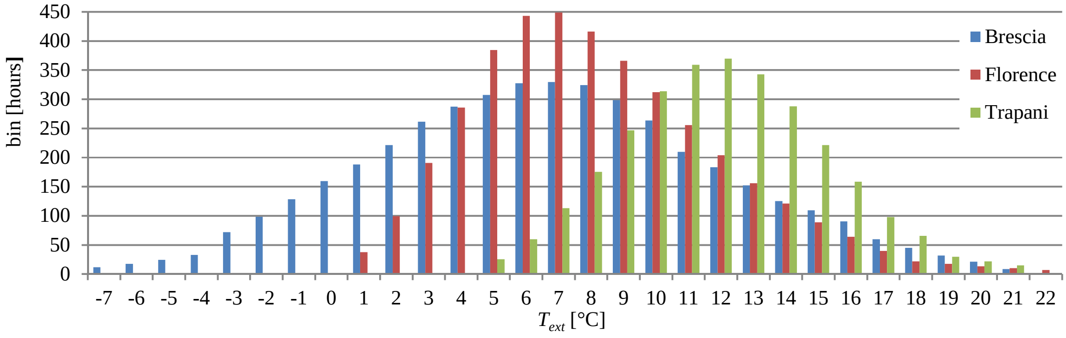

Fig. 1. Bin distribution for the heating season in Brescia, Florence and Trapani (Italy).

By observing the data depicted in Fig. 1 the difference in terms of weather among the selected localities is clear: Brescia, in the North of Italy, is characterized by the lowest external temperature with an outdoor design temperature (T_{des}) equal to -7°C and a mode of the bin distribution equal to 7°C; Florence, North-Center Italy, is characterized by a value of T_{des} equal to 0°C with a minimum external air temperature equal to 1°C (mode 7°C); Trapani, Southern Italy, is characterized by a value of T_{des} equal to 5°C with a minimum external air temperature equal to 5°C (mode 12°C).

3. Building energy signature

As indicated in [9] and [10] the thermal features of a building can be highlighted by means of the Building Energy Signature (BES), which is defined as the thermal power required by the building as a function of the external air temperature (T_{ext}). The method to evaluate the BES is described in the standard EN 15603 [13]. For a building characterized by a linear BES curve, the heating power required by the building in the i^{th} bin, $P_b(i)$, can be evaluated as:

$$P_b(i) = P_{des}\left(\frac{HLET - T_{ext}(i)}{HLET - T_{des}}\right) \tag{1}$$

where HLET (Heating Limit External Temperature) is the value of T_{ext} in correspondence of which the building heating demand becomes zero and P_{des} is the building design load, in correspondence of T_{des}. In the present study, in order to take into account the effects of the building loads on the seasonal heat pumps performances, several linear BES are considered, by fixing the value of HLET at 16°C ([9,10]) and by varying the value of P_{des}. As an example, in Fig. 2 the dashed line represents a BES drawn by considering a building with a thermal load at design conditions (T_{des}=-7°C) equal to 43.13 kW (P_{des}), while the dotted line is representative of a building having a value of the building design load equal to 71.88 kW (P'_{des}). The building energy demand in correspondence of each i^{th} bin can be evaluated by multiplying the corresponding value of $P_b(i)$ by the duration of the i^{th} bin ([8]).

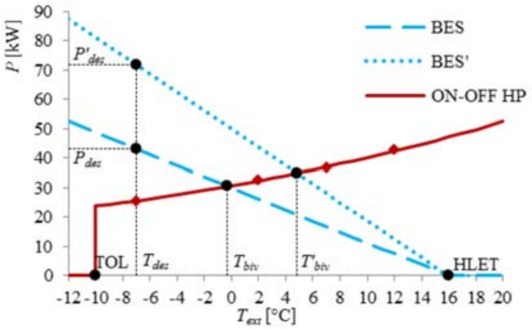

Fig. 2. Examples of BES and characteristic curve of an ON-OFF HP.

4. Heat pump characteristics

The red curve in Fig. 2 represents an example of characteristic curve of an electric air-source mono-compressor ON-OFF Heat Pump (ON-OFF HP), obtained for a fixed value of the temperature T_w of the hot water produced by the heat pump. The curve is stopped in correspondence of the value of T_{ext}, given by the heat pump manufacturer, below which the heat pump is switched off (Temperature Operative Limit, TOL).

The thermal power delivered by the heat pump can be obtained starting from the technical datasheet given by the heat pump manufacturer. The heat pump thermal power is a function of the external air temperature and of the hot water temperature for ON-OFF HPs, but the heat pump capacity is also function of the number of compressors switched on, for a Multi-Compressor Heat Pump (MCHP), or function of the inverter frequency, for an Inverter-Driven Heat Pump (IDHP). The intersection between the BES and the heat pump characteristic curve (corresponding to the maximum number of compressors switched on, for MCHPs, or to the maximum inverter frequency, for IDHPs) is called balance point. The external air temperature corresponding to this point is called bivalent temperature (T_{biv}) and represents the value of the external air temperature in correspondence of which the heat power delivered by the heat pump is equal to the thermal load needed by the building. When T_{ext} is lower than T_{biv} the building heating demand cannot be satisfied by the heat pump and the back-up system must be activated (electric heaters); when T_{ext} is higher than T_{biv} the heat pump power exceeds the building request and, in order to match the energy demand, on-off cycles need to start (ON-OFF HPs) or the number of activated compressors decreases (MCHPs) or the inverter reduces its working frequency (IDHPs). For MCHPs and IDHPs on-off cycles start only if the building energy request is lower than the energy that the heat pump would deliver with only one compressor activated (MCHPs) or at the minimum inverter frequency (IDHPs). This situation corresponds to values of the external air temperature higher than $T_{biv,2}$, which is the value of T_{ext} at which the BES curve meets the heat pump characteristic curve corresponding to only one compressor switched on (MCHPs) or to the minimum inverter frequency (IDHPs).

The heat pump characterization is completed by the characteristic curve of the *COP* at declared capacity, obtainable from the manufacturer data as described in [8]. Tables 1,2 show the data given by the manufacturer for the three air-to-water heat pumps considered in this work. The heat pumps characteristic curves are obtained through interpolations of the heat pump power and *COP* at declared capacity data of Table 2 ([8]). By comparing the data shown in Table 2 it is evident that the heat pumps selected in this work are characterized by very similar values of thermal power delivered at rated conditions.

Table 1. Heat pumps technical data.

Heat pump type	ON-OFF HP	MCHP	IDHP
TOL [°C]	-10	-10	-18
Compressors number	1	2	1
Frequency range [Hz]	50	50	30-120

Table 2. Heat pumps power and *COP* at declared capacity data.

		Power [kW] (COP)				
		ON-OFF HP	MCHP		IDHP	
T_{ext}	T_w		1 compr. on	2 compr. on	min. freq.	max. freq.
TOL	35	23.30 (2.75)	12.30 (2.76)	23.10 (2.70)	5.58 (2.48)	19.90 (1.86)
-7	35	25.50 (3.07)	13.20 (2.95)	25.00 (2.90)	6.87 (3.05)	26.10 (2.85)
2	35	32.70 (3.83)	16.70 (3.71)	31.20 (3.59)	8.68 (3.86)	32.40 (3.49)
7	35	36.60 (4.23)	19.30 (4.26)	34.80 (3.98)	10.00 (4.48)	36.40 (3.91)
12	35	42.60 (4.86)	22.30 (4.89)	40.80 (4.65)	11.60 (5.25)	41.70 (4.45)

5. Results

The seasonal performances of the heat pumps presented in the previous section are evaluated through the mathematical model presented in [8]. For each location (Brescia, Florence and Trapani) different buildings have been considered, changing the BES curve, coupled with the three heat pumps described above.

For each case study the model calculates: the total thermal energy required by the building during the heating season, Q_b; the total thermal energy delivered by the heat pump, Q_{HP}; the total electric energy used by the heat pump, $E_{HP,us}$, and by the back-up system (electric heaters), E_{BU}. The previous total energy values are obtained as sum of the corresponding values of energy evaluated in each i^{th} bin. The mean seasonal *COP* of the heat pump, $SCOP_{net}$, and of the whole system, composed of electric air-to-water heat pump and electric heaters, $SCOP_{on}$, are evaluated according to the following equations:

$$SCOP_{net} = \frac{Q_{HP}}{E_{HP,us}} \qquad\qquad SCOP_{on} = \frac{Q_b}{E_{HP,us} + E_{BU}} \tag{2}$$

The numerical results of some relevant case studies are reported in Table 3. The values of T_{biv}, and, for the MCHP and IDHP, also of the secondary bivalent temperature $T_{biv,2}$, are reported together with the energy values and the seasonal efficiencies obtained numerically. The values of $E_{HP,us}$ in Table 3 show as the ON-OFF HP uses more electric energy than the MCHP and IDHP in similar conditions. The value of E_{BU} is an indication of the level of under-sizing of the heat pump with respect to the building thermal needs; obviously, if the value of E_{BU} is 0, the $SCOP_{on}$ equals the $SCOP_{net}$.

Table 3. Numerical results of some case studies.

T_{des} [°C]	P_{des} [kW]	Heat pump type	T_{biv} [°C]	$T_{biv,2}$ [°C]	Q_b [MWh]	Q_{HP} [MWh]	$E_{HP,us}$ [MWh]	E_{BU} [MWh]	$SCOP_{net}$	$SCOP_{on}$
-7	28.75	ON-OFF HP	-5.26	/	51.21	51.15	17.82	0.066	2.87	2.86
-7	115.00	ON-OFF HP	8.31	/	204.86	126.17	36.41	78.68	3.47	1.78
-7	28.75	MCHP	-4.83	2.45	51.21	51.12	13.96	0.0939	3.66	3.65
-7	115.00	MCHP	8.61	11.59	204.86	121.83	31.31	83.02	3.89	1.79
-7	28.75	IDHP	-5.50	7.79	51.21	51.16	12.49	0.051	4.10	4.08
-7	115.00	IDHP	8.40	13.58	204.86	125.84	32.05	79.01	3.93	1.84
0	30	ON-OFF HP	-0.25	/	58.55	58.55	18.41	0	3.18	3.18
0	110	ON-OFF HP	10.13	/	214.67	129.37	35.16	85.30	3.68	1.78
0	30	MCHP	0.25	6.00	58.55	58.55	14.57	0	4.02	4.02
0	110	MCHP	10.36	12.69	214.67	124.25	30.32	90.42	4.10	1.78
0	30	IDHP	-0.32	10.14	58.55	58.55	13.07	0	4.48	4.48
0	110	IDHP	10.22	14.20	214.67	128.32	31.40	86.35	4.09	1.82
5	34.38	ON-OFF HP	4.81	/	37.54	37.54	10.91	0	3.44	3.44
5	75.63	ON-OFF HP	10.13	/	82.59	71.29	18.26	11.30	3.90	2.79
5	34.38	MCHP	5.22	9.38	37.54	37.52	8.63	0.02	4.35	4.34
5	75.63	MCHP	10.36	12.69	82.59	69.62	15.63	12.97	4.45	2.89
5	34.38	IDHP	4.86	12.26	37.54	37.54	7.66	0	4.90	4.90
5	75.63	IDHP	10.22	14.20	82.59	70.78	15.52	11.81	4.56	3.02

In order to highlight the main results obtained in this work, in Fig. 3-5 the $SCOP_{net}$ and $SCOP_{on}$ trends as functions of the bivalent temperature are shown by varying the building location and the type of heat pump considered. As pointed out by Fig. 3-5, the best *SCOP* values are almost always obtained with the inverter-driven heat pump (IDHP), while the ON-OFF HP gives the lowest results. As highlighted by the bin profiles, drawn in Fig. 3-5 as functions of the external air temperature, the value of the maximum $SCOP_{net}$ and $SCOP_{on}$ depends on the adopted bivalent temperature, which means that there exists an optimal choice of the size of the heat pump for a fixed building and for a fixed location. The highest values of $SCOP_{net}$ and $SCOP_{on}$ are achievable in the hottest climate (Trapani) by selecting an IDHP having a bivalent temperature equal to the design temperature (T_{des}=5°C). This result is confirmed also for Brescia and Florence (Fig. 3,4). It is possible to conclude that the best seasonal performances of an IDHP can be generally obtained by adopting as bivalent temperature the design temperature.

This conclusion is not valid for MCHPs and especially for mono-compressor heat pumps (ON-OFF HPs). In these last cases, the results of Fig. 3-5 demonstrate that, in order to maximize the $SCOP_{on}$, there exist an optimal bivalent temperature, but this value is always larger than the design temperature.

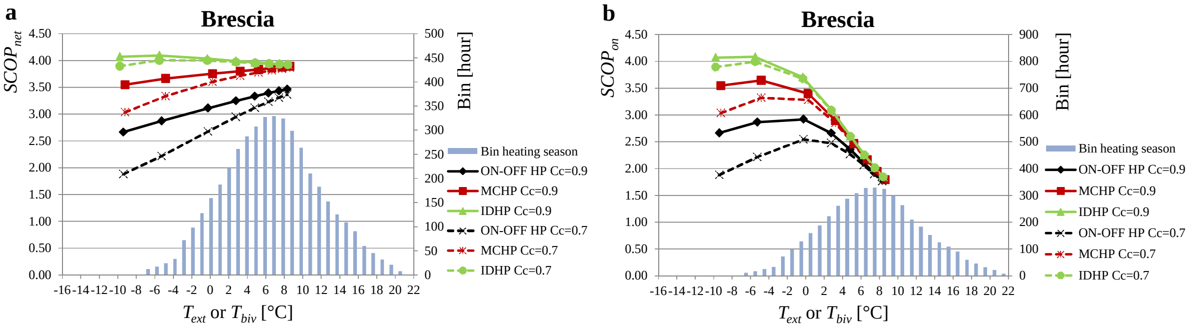

Fig. 3. (a) $SCOP_{net}$ and bin distribution for Brescia; (b) $SCOP_{on}$ and bin distribution for Brescia.

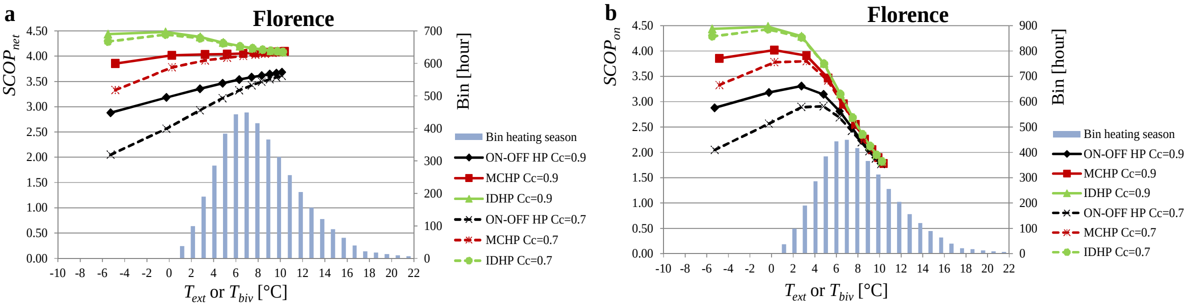

Fig. 4. (a) $SCOP_{net}$ and bin distribution for Florence; (b) $SCOP_{on}$ and bin distribution for Florence.

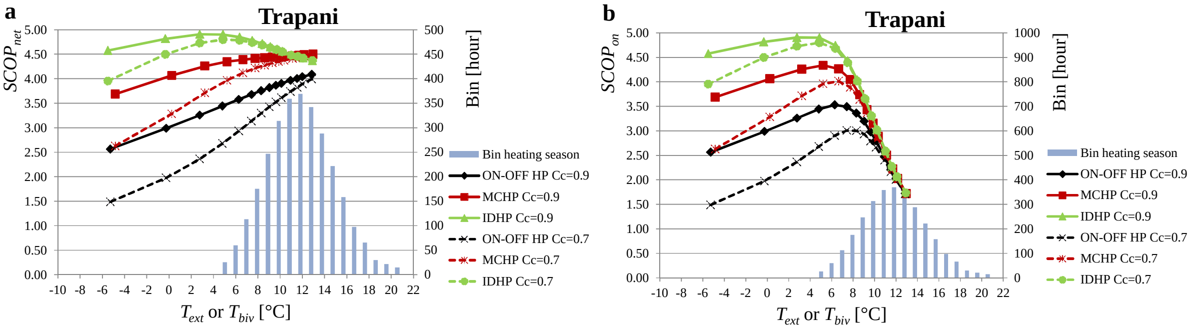

Fig. 5. (a) $SCOP_{net}$ and bin distribution for Trapani; (b) $SCOP_{on}$ and bin distribution for Trapani.

More in detail, in terms of $SCOP_{net}$, the trend is monotonically increasing with the value of T_{biv}, apart from the case of IDHP, for which the $SCOP_{net}$ trend in each climate has a peak in correspondence of a value of T_{biv} equal to the design temperature T_{des}. The $SCOP_{on}$ trend always shows a maximum point in proximity of T_{des} for the IDHP;

the peak moves to larger values of the bivalent temperature for the MCHP and ON-OFF HP; the value of the external air temperature which maximizes the $SCOP_{on}$ becomes higher for hotter climates.

The difference in both the $SCOP_{net}$ and $SCOP_{on}$ values caused by the different types of heat pumps becomes more and more negligible with the increasing of T_{biv}.

The *SCOP* values of the dashed lines in Fig. 3-5 have been obtained, in comparison with the *SCOP* values of the continuous lines, by adopting a different value of the degradation coefficient, C_c, linked to the behavior of the heat pump when on-off cycles are activated ([9]). In fact, for each i^{th} bin, in order to take into account the degradation of the heat pump *COP* in case the on-off cycles occur, the standard EN 14825 suggests to multiply the obtained value of the *COP* at declared capacity by the *COP* correction factor, f_{COP}, defined in Eq. (3):

$$f_{COP}(i) = \frac{CR(i)}{1 - C_c + C_c \ CR(i)} \tag{3}$$

CR (*i*) in Eq. (3) is the heat pump capacity ratio, namely the ratio between the thermal power delivered by the heat pump and the maximum power which the heat pump could deliver in the i^{th} bin conditions ([8]). The numerical value of the degradation coefficient C_c in Eq. (3) must be experimentally quantified by the manufacturer, but, in absence of indications, the standards [9,10] suggest to use a value of C_c equal to 0.9: this value of C_c has been used for the evaluation of the *SCOP* shown in Fig. 3-5 with continuous curves.

However, as demonstrated in [7], the value of C_c suggested by the standards has proved to be too optimistic in order to take into account the real losses linked to the impact of the on-off cycles on the *COP* of a real heat pump.

As a consequence, the same calculation has been repeated by considering a value of C_c equal to 0.7 (as suggested in [7]) and the obtained *SCOP* values are shown by using dashed curves in Fig. 3-5. In this way it is possible to highlight the impact of the degradation coefficient on the evaluation of the seasonal performances of the air-source heat pumps when the sizing conditions are changed. Obviously, the degradation coefficient value is more influent on the value of the *SCOP* for ON-OFF HPs, with respect to MCHPs or IDHPs, as, for external air temperatures higher than T_{biv}, on-off heat pumps must start the on-off cycles in order to follow the building demand, while, for MCHPs and IDHPs, the on-off condition is avoided until T_{ext} is higher than $T_{biv,2}$.

The difference between the $SCOP_{on}$ values obtained with C_c equal to 0.9 with respect to the ones calculated in the same conditions with C_c equal to 0.7 ranges from 0%, for the case of a IDHP at Trapani with T_{biv}=12.92°C, up to 42% for the case of an ON-OFF HP at Trapani with T_{biv}=-5.26°C. The role of the degradation coefficient becomes relevant when the selected bivalent temperature T_{biv} is low, which means that C_c is important when heat pumps over-sized with respect to the building needs are adopted. A lower value of T_{biv}, in fact, corresponds to a lower value of $T_{biv,2}$ (which represents the maximum external air temperature for which the on-off cycles can be avoided); obviously, $T_{biv,2}$ coincides with T_{biv} for a mono-compressor heat pump (ON-OFF HP).

The difference between the results obtained with the different C_c values is also enhanced at hotter climates (see Fig. 5 and Fig. 3), in which the bin distribution is shifted to higher temperatures, with a consequent increase of the number of the seasonal on-off cycles.

6. Conclusions

A mathematical model for the evaluation of the seasonal efficiency of heating systems based on electric air-to-water heat pumps integrated by electric heaters is used in this paper to analyze the seasonal coefficient of performance, *SCOP*, as a function of the climate, of the building thermal needs and of the heat pump type (on-off heat pump (ON-OFF HP), multi-compressor heat pump (MCHP) or inverter-driven heat pump (IDHP)). The numerical results highlight that, to enhance the seasonal efficiency of the system, there exists an optimal value of the bivalent temperature, which is linked to the choice of the heat pump size with respect to the building. The numerical results show that IDHPs allow to reach the highest values of *SCOP* and the optimal sizing of the IDHP is obtained when the bivalent temperature is selected as equal to the design temperature. Also in the case of MCHP and ON-OFF HP there exists an optimal value of the bivalent temperature which maximizes the system performance, but it is larger than the design temperature. The results presented in this paper demonstrate that the degradation coefficient of the heat pump can have a strong influence on the *SCOP*, especially for ON-OFF HPs installed in hot climates and adopting a low bivalent temperature.

Acknowledgements

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