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Annual performances of reversible air source heat pumps for space conditioning

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Abstract

The paper presents the results obtained by a numerical simulation of a heating and cooling system based on a reversible air-to-water electric heat pump and electric resistances as back-up. According to the procedure suggested by the current standards EN 14825 and UNI/TS 11300-4, by using the bin method the influence of outdoor conditions and of the typology of heat pump installed has been investigated by determining the value assumed by the seasonal coefficient of performance ($SCOP_{on}$), the seasonal efficiency ratio (*SEER*) and the annual performance factor (*APF*). The numerical results allow discussing the rules for an optimal heat pump sizing in a fixed site.

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Keywords: air-to-water heat pumps; reversible heat pumps; seasonal performances; APF; residential buildings

1. Introduction

In recent years the European Commission published a set of Directives to promote the use of renewable energy and to achieve energy savings in buildings. Reversible heat pumps are able to provide thermal energy for space conditioning and for domestic hot water production in a single unit, by consuming less primary energy with respect to traditional systems.

Heat pumps seasonal performances are strongly affected by a series of parameters, as indoor/outdoor heat source temperature, system modulation capability, heating and cooling load, sizing. Recently some researchers have investigated the influence of the above-mentioned factors on heat pump efficiency[1-3]: different climates have been

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selected in [1-2] in order to analyze how outdoor conditions affect air heat pumps seasonal performances, while [3] reports the effect of the heat pump behavior at partial load on Seasonal Coefficient of Performance (*SCOP*).This work has the aim to show how the seasonal and annual performances of different kinds of reversible air-to-water heat pumps located in various Italian sites can be optimized by means of the correct choice of the system sizing.

2. Methodology

In this section the methodology for the assessment of the seasonal and yearly performances of electric-driven air source heat pumps (HP) is described. The mathematical model presented in [3] is followed in order to calculate the performances for residential buildings space heating and cooling of different HPs typologies: mono-compressor ON-OFF heat pumps (ON-OFF HPs), multi-compressor heat pumps (MCHPs) and inverter-driven heat pumps (IDHPs).

2.1. Building and climates characterization

As suggested by the Italian standard UNI TS 11300-4 [4] and the European Standard EN 14825 [5], the seasonal performance of reversible air-source HPs during the heating season ($SCOP_{on}$) and the Seasonal Energy Efficiency Ratio (*SEER*) during the cooling season, can be evaluated numerically by means of the bin method.

In order to determine the yearly performance of air-source HPs the bin distributions of the outdoor temperature related to both heating and cooling season are needed. As pointed out by [6], the bin trend for a specific site can be calculated: (i) by using the hourly outside temperature distribution of the Test Reference Year (TRY) of the location; (ii) by using the procedure defined by the Italian Standard UNI TS 11300-4. In this paper the bin distribution of the heating season is calculated with the UNI TS 11300-4 method, while bins of the cooling season are determined by using the TRY weather data for the selected Italian sites.

In order to simulate the behavior of the reversible air-to-water HP as a function of the seasonal heating and cooling loads, a real two-flat residential building, composed by 12 apartments and built in 1983, has been selected. The main data of the building are summarized in Table 1.

Table 1. Geometric and thermal characteristics of the selected building

Useful floor area [m^2]	Total dispersing surface [m^2]	Total surface of windows [m^2]	Net conditioned volume [m^3]	S/V ratio	External wall U-value [W/m^2 K]	Windows U-value [W/m^2 K]
787	1416	139	2125	0.52	0.69	4.50

In order to evaluate the effects of different weather data on the annual efficiency of the system and on the HP sizing rules-of-thumb, the building has been considered in three different Italian locations: Milan (45.5° N, 9.2° E), Rome (41.9° N, 12.4° E) and Palermo (38.1° N, 13.3° E).

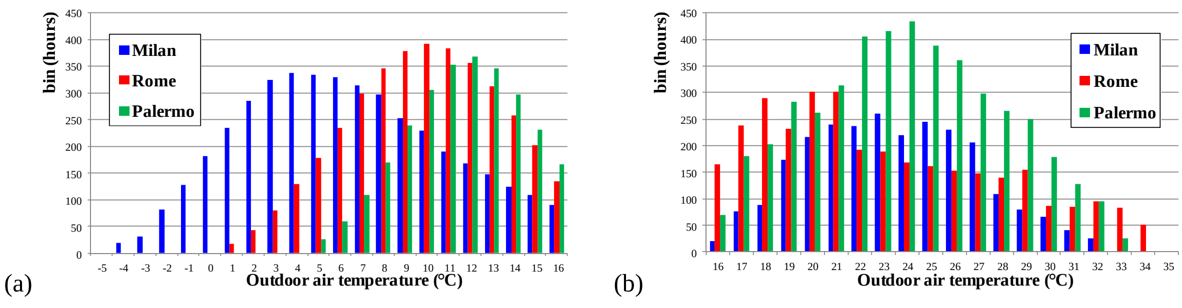

Fig. 1. Bin trend for the selected climates during the heating season (a) and the cooling season (b).

The bin distribution of the selected locations presents different trends. As shown in Fig. 1a the heating season in Milan is the coldest among the selected climates with a design temperature $T_{des,h}$ of -5°C and an average temperature

$T_{avg,h}$ of 6.8°C. Rome and Palermo are characterized by a warmer heating season: they have a $T_{des,h}$ equal to 0°C and 5°C, respectively, and $T_{avg,h}$ equal to 10.3°C and 12.1°C, respectively.

As pointed out by Fig 1b, the hardest cooling design condition for the HP is set in Rome, with a value of the design temperature $T_{des,c}$ of 34°C and a value of the average temperature $T_{avg,c}$ of 24.3°C. Milan and Palermo are characterized by similar design and average values ($T_{des,c}$ equal to 32°C and 33°C and $T_{avg,c}$ equal to 23.6°C and 24.3°C, respectively) but in Palermo the number of hours in which the outdoor temperature is larger than 24°C is very high if compared with Milan.

The calculation of the building net thermal energy needs for space heating and cooling ($E_{month,h}$ and $E_{month,c}$, respectively) is performed on a monthly basis with the method described in the Italian Standard UNI TS 11300-1[7].

Considering an operating time of 24 h/day during the whole heating and cooling season, it is possible to evaluate the monthly average thermal load of the building ($P_{month,h/c}$) which the HP must cover. The average thermal load can be correlated to the corresponding monthly average outdoor temperature. In Fig. 2a,b the $P_{month,h/c}$ values are shown as a function of the outdoor monthly average temperature; the linear interpolation of these data gives the building energy signature (BES) both for heating and cooling season, as described in UNI EN 15603 [8]. From BES it is possible to obtain the design thermal loads of the building for the different locations.

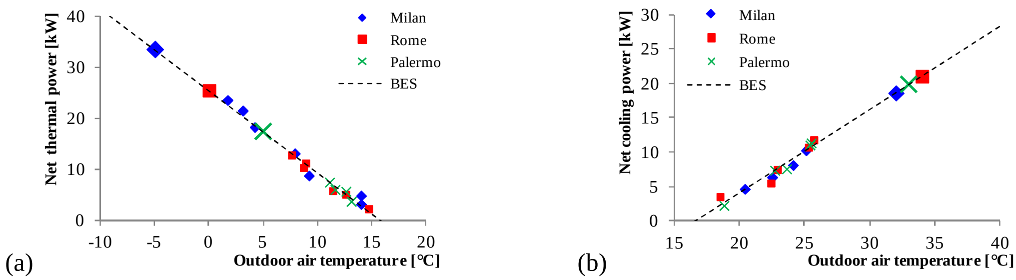

Fig. 2. Building energy signature for the selected climates for heating (a) and cooling (b) season

Table 2 summarizes the values of design temperature and design load for the three selected locations deducted by using the BES and the main differences among the sites, highlighted by the heating and cooling degree days.

Table 2. Design temperatures, design loads and weather characteristics for the selected climates

	Design Temperature [°C]		**Design Load [kW]**		**Length of the Season**		**Degree Days**	
	Heating	Cooling	Heating	Cooling	Heating	Cooling	Heating	Cooling
Milan	-5	32	33.6	18.6	15/10-15/04	01/06-15/09	2404	145
Rome	0	34	25.5	21.1	01/11-15/04	15/05-30/09	1415	299
Palermo	5	33	17.4	19.8	01/12-31/03	01/05-30/09	751	304

2.2. Heat pumps and thermal plant characteristics

The thermal plant is considered fed by a single reversible air-to-water HP coupled to fan-coils and working with a fixed outlet water temperature of 45°C in heating mode and 7°C in cooling mode. During the heating season electric heaters are selected as back-up system (bivalent mono-energetic heating system) while during the summer no back-up systems have been considered.

For each location, different models of reversible HPs have been considered. The main features of the eleven HPs selected in this work are summarized in Table 3 where the full load performances of the HPs declared by the manufacturer are reported for a set of outdoor temperatures between -7°C and 12°C (heating mode) and between 20°C and 35°C (cooling mode).

Table 3. Heat pumps performances at full load declared by the manufacturer (heating: water temperature=45°C; cooling: water temperature=7°C)

HP typology	#	Frequency range [Hz]	N° of compressors	T_{ext} [°C]	-7	2	7	12	T_{ext} [°C]	20	25	30	35
ON-OFF HP	1	-	1	P_{th} [kW]	17.8	20.6	22.9	25.7	P_f [kW]	22.3	21.2	20.2	19.2
				COP	2.57	2.98	3.30	3.68	EER	4.27	3.72	3.23	2.79
ON-OFF HP	2	-	1	P_{th} [kW]	20.0	23.6	27.0	31.0	P_f [kW]	27.2	26.1	24.7	23.3
				COP	2.56	2.96	3.33	3.76	EER	4.30	3.80	3.32	2.88
ON-OFF HP	3	-	1	P_{th} [kW]	21.9	25.9	29.8	34.3	P_f [kW]	31.0	29.5	27.8	26.1
				COP	2.58	2.97	3.36	3.81	EER	4.31	3.76	3.26	2.79
ON-OFF HP	4	-	1	P_{th} [kW]	26.4	31.6	36.3	41.1	P_f [kW]	35.9	34.3	32.7	30.9
				COP	2.63	3.08	3.48	3.90	EER	4.31	3.82	3.38	2.92
MCHP	5	-	2	P_{th} [kW]	14.6	19.1	22.2	25.6	P_f [kW]	21.8	20.8	19.9	18.8
				COP	2.47	3.04	3.36	3.67	EER	4.74	4.20	3.73	3.24
MCHP	6	-	2	P_{th} [kW]	16.7	21.8	25.1	29.1	P_f [kW]	25.3	24.2	22.8	21.6
				COP	2.42	2.97	3.31	3.71	EER	4.85	4.23	3.67	3.18
MCHP	7	-	2	P_{th} [kW]	20.0	26.0	30.1	34.8	P_f [kW]	30.7	29.3	27.3	26.4
				COP	2.48	3.00	3.35	3.75	EER	4.64	4.08	3.57	3.11
MCHP	8	-	2	P_{th} [kW]	24.6	32.1	37.3	43.0	P_f [kW]	37.1	35.6	34.0	32.4
				COP	2.49	3.05	3.42	3.80	EER	4.67	4.15	3.66	3.20
IDHP	9	20-120	1	P_{th} [kW]	15.1	18.6	21.2	24.6	P_f [kW]	21.9	20.9	19.7	18.5
				COP	2.11	2.52	2.82	3.22	EER	3.83	3.37	2.89	2.46
IDHP	10	20-120	1	P_{th} [kW]	21.3	26.1	29.6	33.8	P_f [kW]	30.7	29.4	28	26.6
				COP	2.17	2.60	2.91	3.31	EER	4.07	3.55	3.08	2.66
IDHP	11	20-120	1	P_{th} [kW]	24.4	30.1	33.2	38.6	P_f [kW]	34.4	32.9	31.3	29.6
				COP	2.14	2.55	2.78	3.19	EER	3.81	3.31	2.86	2.45

It is important to highlight that the heating load is larger than the cooling load (in absolute value) in Milan and Rome; this fact means that a HP able to cover exactly the peak cooling load results generally undersized for the heating season. In this analysis for Milan and Rome the coverage of the building peak heating load has been varied by considering different HPs having a larger nominal thermal power; in this way, the oversizing of the HP during the cooling season increases and the effect of this oversizing on the yearly efficiency of the system can be appreciated numerically. For the building located in Palermo the sizing of the HP is based on the cooling peak and the effect of the HP control system is checked by comparing the yearly performances obtainable by using different HP typologies (ON-OFF HP, MCHP and IDHP).

3. Results

According to the procedure described in [3] the seasonal and the annual energy performance of the HVAC system based on a reversible air-to-water HP with electric back-up during the heating season have been evaluated, both in heating and cooling mode, by calculating the value assumed by the $SCOP_{on}$ during the heating season, the *SEER* during the cooling season and finally the Annual Performance Factor (*APF*) defined as follows:

$$SCOP_{on} = \frac{Q_{HP,h} + Q_{BU,h}}{E_{HP,a,h} + E_{BU,a,h}}\ ;\ SEER = \frac{Q_{HP,c}}{E_{HP,a,c}}\ ;\ APF = \frac{Q_{HP,h} + Q_{BU,h} + Q_{HP,c}}{E_{HP,a,h} + E_{BU,a,h} + E_{HP,a,c}} \quad (1)$$

where Q_{HP} and Q_{BU} are the thermal energy delivered by the HP and the back-up system, respectively, E_{HP} and E_{BU} are the electric energy absorbed by the HP and the back-up system, respectively, and the subscripts h and c mean respectively heating and cooling.

The main output data of each simulation are summarized in Table 4: for each test case, the design thermal power of the HP, the oversizing degree of the system with respect to the design heating and cooling load (see Table 2), $SCOP_{on}$, *SEER*, *APF* and the bivalent temperature both for heating ($T_{b,h}$) and cooling ($T_{b,c}$) mode are indicated.

Table 4. Oversizing, seasonal and yearly performances of the selected heat pumps

City	**#**	**Unit Capacity at T_{des} [kW]**		**Oversizing**		**$T_{b,h}$ [°C]**	**$SCOP_{on}$**	**$T_{b,c}$ [°C]**	***SEER***	***APF***
		Heating	Cooling	Heating	Cooling					
Milan	1	17.8	19.8	-47%	+6%	2.9	2.60	32.87	3.27	2.74
	2	20.0	24.2	-40%	+30%	1.45	2.72	35.81	3.18	2.82
	3	21.9	27.4	-35%	+47%	0.43	2.79	37.62	3.05	2.85
	4	26.4	32.0	-21%	+72%	-1.89	2.89	40.74	2.97	2.91
	5	15.5	19.5	-54%	+5%	3.5	2.60	32.62	3.93	2.84
	6	17.7	22.4	-47%	+20%	2.29	2.74	34.64	3.76	2.94
	7	21.2	27.0	-37%	+45%	0.47	2.98	38.09	3.66	3.16
	8	26.1	33.4	-22%	+80%	-1.89	3.13	41.88	3.31	3.17
	9	15.7	19.2	-53%	+3%	3.83	2.32	32.46	4.31	2.62
	10	22.2	27.5	-34%	+48%	0.34	2.76	38.1	4.03	3.00
	11	25.4	30.6	-24%	+65%	-1.22	2.83	39.83	4.00	3.05
Rome	1	19.7	19.4	-23%	-8%	2.86	2.96	32.75	3.15	3.04
	2	22.4	23.6	-12%	+12%	1.41	2.90	35.68	3.08	2.97
	3	24.6	26.4	-4%	+25%	0.39	2.86	37.49	2.95	2.89
	5	18.0	19.0	-29%	-10%	3.47	3.32	32.5	3.79	3.50
	6	20.5	21.8	-20%	+3%	2.26	3.25	34.51	3.64	3.41
	7	24.5	26.5	-4%	+26%	0.43	3.29	37.93	3.53	3.39
	9	17.6	18.7	-31%	-11%	3.79	3.09	32.35	3.86	3.37
	10	24.8	26.9	-3%	+27%	0.3	3.11	37.95	3.91	3.40
Palermo	1	21.9	19.6	+26%	-1%	2.78	2.86	32.85	3.24	3.11
	5	20.9	19.2	+20%	-3%	3.40	3.44	32.59	3.91	3.76
	9	20.1	19.0	+16%	-4%	3.72	3.34	32.43	4.13	3.85

As an example, the first case simulated for Milan is related to the selection of an ON-OFF HP(#1) which is able to cover exactly the cooling load (+6%, the heat pump is slightly oversized in cooling mode) but strongly undersized for the heating season (-47%). In this case the system is characterized by good values of the *SEER* during the summer (3.27) but the performance of the HP during the winter is low with a $SCOP_{on}$ equal to 2.6 due to the large use of the electric resistances. If a MCHP or a IDHP are considered having similar features of case #1 the results in terms of $SCOP_{on}$ underline that the replacement of the ON-OFF HP (#1) with the MCHP (#5) is not influent in terms of $SCOP_{on}$; on the contrary, the IDHP (#9) determines a decrease of $SCOP_{on}$ (-11%) due to the increase of the bivalent temperature (3.83°C vs 2.9°C). On the contrary, *SEER* improves significantly if the ON-OFF HP (#1) is replaced by a MCHP (#5, +20%) or by a IDHP (#9, +32%). It is interesting to note that the results in terms of *APF* highlight how this factor is more linked to the trend of $SCOP_{on}$ than to the trend of *SEER* in locations where Heating degree days are larger than Cooling degree days, like in Milan (see Table 2),

In a cold climate like in Milan the HP sizing is generally based on the peak heating load. This evidence leads to consider units #4, #8 and #11 as the right sized models for this application. Looking the cooling season, the considered HPs result largely oversized for cooling needs (up to 80%). The value of $SCOP_{on}$ goes from 2.89 (ON-OFF HP, #4) to 3.13 (MCHP, #8) and 2.83 (IDHP, #11), larger values with respect to the cases analyzed before with HPs sized on the cooling needs (#1, #5, #9). In terms of *SEER*, HPs #4, #8 and #11 have a reduced performance during the cooling season. In terms of *APF*, in Milan HPs sized on the heating needs (#4, #8, #11) are characterized by larger *APF* with respect to HPs sized on the cooling loads (#1, #5, #9) with an increase of +6% for ON-OFF HP, +12% for MCHP and +16% for IDHP.

Scaling towards smaller models the oversizing in the cooling season drops to zero while simultaneously the heating load is not entirely satisfied by the HP. The seasonal performance indexes have opposite trends: passing from larger to smaller units *SEER* increases according to a minor influence of the on-off cycles; on the contrary, $SCOP_{on}$ decreases because the back-up system delivers a larger amount of thermal energy.

Rome is characterized by a warmer weather with respect to Milan but the heating season is still more severe than the cooling season: also in this site the HP sizing is generally based on the heating peak. The results point out that the best yearly efficiency is obtained with the smaller units (#1, #5, #9), sized on the cooling peak load. IDHPs are characterized by a different trend: as reported by [3] inverter-driven units present the best efficiency when they are oversized with respect to thermal loads and the results of this work confirm this evidence.

Due to its weather features, in Palermo the HP sizing is generally based on the cooling peak; in fact, this site is characterized by a heating peak load lower than the cooling peak load (see Table 2). This means that a unit sized on the cooling load in Palermo is generally oversized for the heating mode. In this case only one model of HP for each typology has been considered (#1, #5, #9). Among the HPs considered it is evident that the IDHP is characterized by the largest value of *APF* with respect to similar ON-OFF HPs and MCHPs; IDHPs are able to give larger $SCOP_{on}$ during the winter, since a slight oversizing is beneficial for this kind of HP, as well as larger *SEER* during the summer. From the data reported in Table 4 it is possible to see how in Palermo *APF* reaches its maximum values: in this site the yearly performance factor by using IDHPs is higher of about +13% and +30% with respect to Rome and Milan respectively, for MCHPs it is higher of +10% and +20% compared to Rome and Milan, and about +3% and +7% higher for ON-OFF HPs with respect to Rome and Milan.

4. Conclusions

This paper reports the results of a series of simulations aimed to evaluate seasonal and yearly performances of heat pump systems coupled to residential buildings. Different kinds of heat pumps and different climates have been considered in order to highlight the influence of these parameters on the annual efficiency of the system. Results show that in Italy in the Northern and Middle regions, where the heating loads are larger than the cooling loads, the best annual performances are reached by selecting MCHPs or IDHPs sized to cover partially the heating peak load with a bivalent temperature of the order of 0-2°C. On the contrary in the Italian Southern regions the heat pump must be sized on the cooling peak loads and in this case, if the heating load is of the same order of magnitude of the cooling loads (or lower) IDHPs can be the best choice in order to optimize the Annual Performance Factor.

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