The bin method to investigate the effect of climate conditions on the SCOP of air source heat pumps: the Italian case

EUGENIA ROSSI DI SCHIO, VINCENZO BALLERINI, PAOLO VALDISERRI
Department of Industrial Engineering
Alma Mater Studiorum – Università di Bologna
Viale Risorgimento 2, I-40136 Bologna
ITALY

Abstract: The paper investigates the seasonal performances of electric air-to-water heat pumps specifically related to climatic conditions of the place where the heat pump is installed. The analysis is carried out using easily available weather data for some Italian towns differently located, and using the bin-method proposed by UNI/TS 11300-4. Two different types of heat pumps (on-off and inverter-driven variable speed compressor) are considered and comparisons between different types of heat pumps and different places of installation are performed. The analysis shows that the climate of the installation place is the most important factor that affects seasonal indexes of heat pumps; moreover, as expected, inverter heat pumps better perform than on-off ones.

Key-Words: bin method, air-source heat pump, decarbonization, climate conditions

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1 Introduction

It was Lord Kelvin who first proposed a practical heat pump system, or "heat multiplier" [1]. Nowadays, there is a need to increase the reduction of greenhouse gas emissions from space heating and cooling in order to meet decarbonization goals. For this reason, heat pumps are becoming increasingly utilized all around the world [2].

In a recent report dealing with decarbonizing space heating by employing air source heat pumps (ASHPs) [3], the authors conclude that ASHPs are cost-competitive today in places where the climate is mild and that, *"with climate policies consistent with rapid decarbonization and reasonably foreseeable technological progress, air-source heat pumps are the low-cost option for typical residential buildings across much of the US by the mid-2030s."* Duicu's study [4] reported the advantages of using heat pumps as a renewable source of energy.

Different studies are also related to the employment of ground sources heat pumps [5]; in those applications, the performance of the entire heating and cooling system is significantly affected by soil thermal properties [6] and the circuit arrangement of the ground heat exchanger [7].

Regarding ASHP, in the recent literature, the effects of climate conditions are investigated by Mouzeviris and Papakostas [8] with reference to Greece. The authors study the seasonal coefficient of performance in heating (SCOP) of 100 different ASHPs from 12 manufacturers, in a range of heat pumps' thermal capacity up to 50 kW. They conclude that the seasonal performance of the various models examined is affected by the heating capacity, the local climate, the supply water temperature, the compressor's technology, and the control system.

Pospisil et al. [9] evaluated the real seasonal coefficient of performance (SCOP) of air-to-water heat pumps operating in Central Europe. The aim of their study is the identification of a possible increase in SCOP of the air-to-water heat pump with a predictive regulation, mainly employing the ASHP during the warmer period of the day with the addition of an accumulation system.

The seasonal performance of electric air-to-water heat pumps is also investigated in [10], by comparing an on-off heat pump with an inverter-driven variable speed compressor. Reference is made to a heat pump for domestic space heating installed in Bologna, and the bin method proposed by UNI/TS 11300-4 [11] is employed in order to investigate the effect of external temperature.

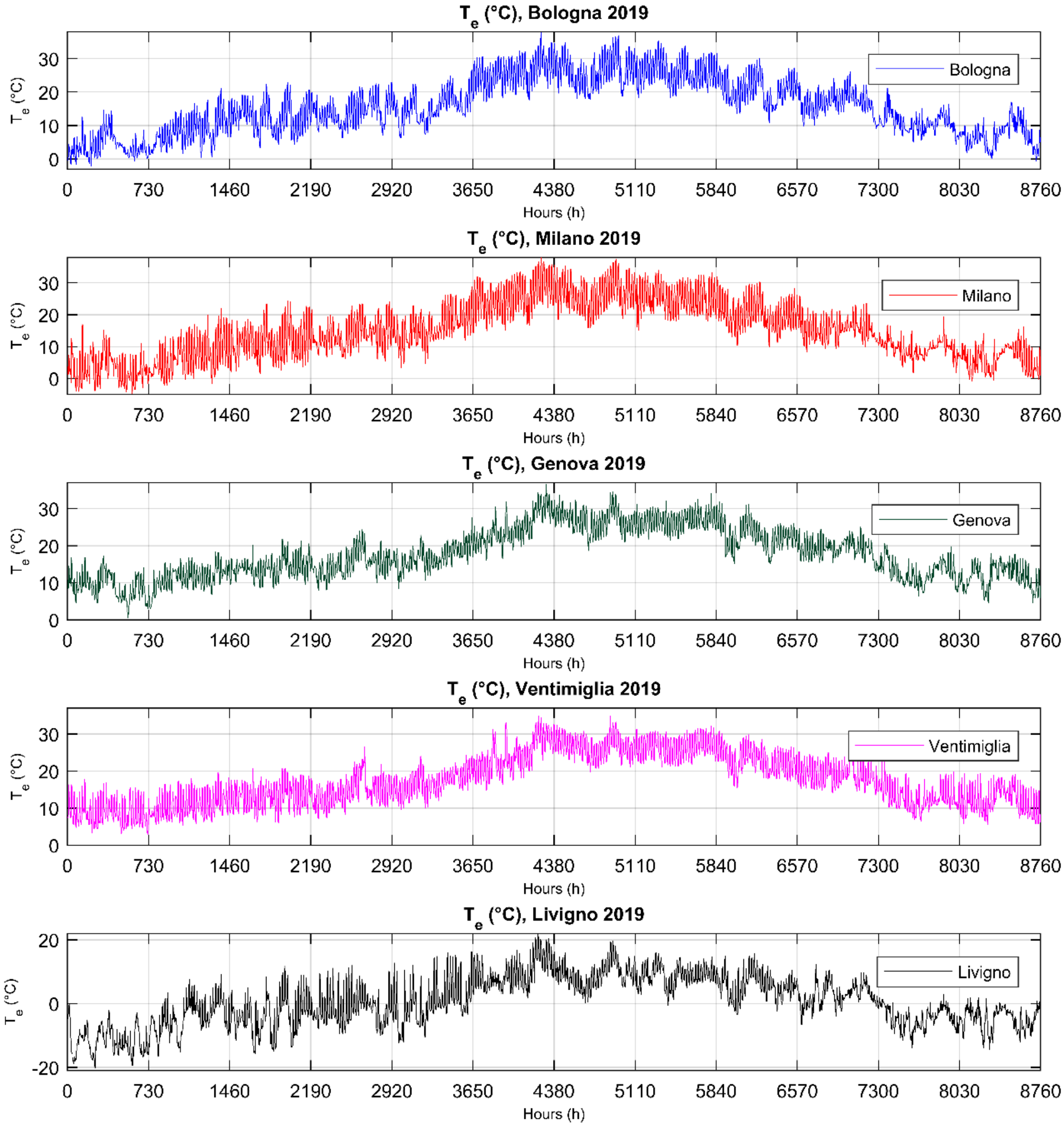

Fig. 1 - Hourly mean air temperature distributions, year 2019

ASHPs are also characterized by the frost formation on the external heat exchanger during winter operation. In a recent study [12] the effect of real climate data on the seasonal coefficient of performance of ASHPs are investigated considering three different heat pump systems coupled with the same building located in three different Italian municipalities. The authors conclude that the electrical energy absorbed by the HP considering defrost is higher with respect to the case with no defrost every year mainly in the localities where the average relative humidity is higher.
In Italy, the recent introduction of Italy's new Superbonus [13], providing a 110% tax discount, can be seen as a very ambitious heat pump installation scheme to date. In [14], a general analysis of the Italian energy system is performed, focusing on the possible energy, environmental, and economic effects that the utilization of individual heat pumps for winter heating can produce.
In the present study, the authors investigate electric air-to-water heat pump performances specifically related to climatic conditions of the place where the heat pump is installed. The analysis is carried out using easily available weather data for a lot of Italian towns and using the bin method proposed by UNI/TS 11300-4. Two different types of heat pumps (on-off and inverter-driven variable speed compressor) and

five Italian towns characterized by different weather conditions were considered (Milano, Bologna, Genova, Livigno and Ventimiglia). The main aims are the evaluation of seasonal performances of the heat pumps related to the weather of the place where the thermal machine is placed and to establish comparisons between different types of heat pumps and different places of installation.

2 Setting of the analysis

The analysis is carried out using the bin-method proposed by UNI/TS 11300-4, and on account of weather data easily available for a lot of Italian towns. In detail, we refer to five Italian towns characterized by different weather conditions (Milano, Bologna, Genova, Livigno and Ventimiglia) and we consider different types of heat pumps (on-off and inverter-driven variable speed compressors).
Technical data related to the heat pumps under investigation, such as the maximum output thermal power and COP (Coefficient Of Performance), are obtained from the product datasheets for different outdoor air temperatures and for different water delivery temperatures.
The most important parameter for the analysis is the mean outdoor air temperature of the place where the heat pump (HP) is installed. The hourly mean air temperature t_e for the five towns previously mentioned are obtained from ARPA (Regional Environmental Protection Agency) website of the specific Italian region (ARPA Lombardia for Milano and Livigno, ARPAE for Bologna and ARPAL for Genova and Ventimiglia). Downloaded data have been further processed to obtain exploitable parameters for the analysis. Temperature data are obtained for the five cities with reference to the year 2019; moreover, for Bologna, Livigno, and Milano data for years 2017 and 2018 are used as well, in order to determine seasonal performance variations from one heating season to another.
Values of hourly mean air temperature are shown in Fig. 1. An initial examination restricted to January 2019 underlines that Genova and Ventimiglia have a similar climate with oscillation of around 8°C; Bologna and Milano have a similar climate instead, but with oscillation of around 3°C, and finally Livigno has a cold climate, with an average monthly air temperature of -11°C.

2.1 Methodology

Attention is paid to two electric air-to-water heat pumps, one on-off HP and the other one an inverter-driven variable speed compressor HP, combined with auxiliary electric resistances (mono-energetic bivalent operating mode heating system). The auxiliary heat source (electric resistances) switches on only for high thermal demand, typically when the outdoor air temperature is low, close to design temperature t_{des}.
Seasonal performance indexes analyzed are $SCOP_{on}$ and *SCOPnet*. $SCOP_{net}$ is defined as the ratio between thermal energy supplied by the heat pump $Q_{th,HP}$ and the electric energy input to the heat pump $EE_{in,HP}$:

$$SCOP_{net} = \frac{Q_{th,HP}}{EE_{,HP}} \tag{1}$$

In $SCOP_{on}$ performance index also the auxiliary energy related to the electric resistances for heating is considered, thus giving:

$$SCOP_{on} = \frac{Q_{th,HP}+Q_{th,BU}}{EE_{,HP}+EE_{,BU}} \tag{2}$$

where $Q_{th,BU}$ is the thermal energy supplied by the resistances and $EE_{in,BU}$ is the electric energy input to the auxiliary resistances.
We assume that the thermal power requested by the building to the heating system linearly decreases for increasing values of the outdoor air temperature and that no power is requested for $t_e \geq 16$°C. Energy analysis is set up for the same two HPs virtually placed in the five towns mentioned above. Since the heat pump power output depends on the outdoor air temperature, we can state that generally, the power output of the heat pump installed in a place with a warm climate (Genova, Ventimiglia) is higher than the power output of the same heat pump installed in a place with cold climate (Livigno). To meet the sizing limit of the machine, we may assume a different power demanded by the building to the heating system, which varies from one place to another.

Table 1 – Design temperature, power requested to the heating system, and power of the auxiliary resistances.

City	t_{des} (°C)	Thermal power requested (kW)	Auxiliary power (kW)
Livigno	9	5	2
Bologna	-5	7	2
Milano	-5	7	2
Genova	0	8	3
Ventimiglia	0	8	3

The buildings in Ventimiglia and Genova request the maximum power whilst Livigno the minimum, as shown in Table 1, where t_{des} is the design temperature for the heating system. *COP* also depends on the capacity ratio *CR*, defined as the ratio between the thermal power supplied by the HP at a specific t_e and the maximum thermal power that the HP can supply at the same t_e. In the analysis, hot water delivery temperature is set constant and equal to 35°C, thus allowing the *COP* to vary only on t_e and *CR*. We obtain the COP_D values (at CR=1) and the thermal power supplied for different t_e, from the HP datasheets, as shown in Table 2, both for the on-off and inverter heat pump considered.

Table 2 – Data from datasheet of on-off and inverter heat pump.

	ON-OFF HP		INVERTER HP	
t_e (°C)	Maximum power (kW)	COP_D	Maximum power (kW)	COP_D
-7	5.09	2.51	5.43	2.86
2	6.15	3.25	5.67	2.96
7	8.67	4.09	8.06	3.92
12	10.24	4.26	9.23	4.37
15	10.83	4.31	9.74	4.56

The heat pump will operate at partial load (below its maximum rated capacity) over a long period during the heating season. This aspect affects the *COP* and is taken into account by introducing the coefficient f_{COP} , according to UNI EN 14825 [15] defined as

$$f_{COP} = \frac{CR}{1-C_c+C_cCR} \tag{3}$$

In Eq. (3) C_C is a degradation coefficient and in absence of further data from heat pump datasheet, C_C =0.9. With reference to the two HPs considered, punctual values of f_{COP} have been provided by manufacturer and *COP* at part load (COP_{PL}) is given by

$$COP_{PL} = f_{COP}COP_D \tag{4}$$

In Fig. 2 the *COP* of the on-off heat pump is reported versus of t_e and *CR*. Since the *COP* variations strongly affect the seasonal performance both a monthly and daily analysis would be inaccurate since a great variation of t_e may occur during the day as well.

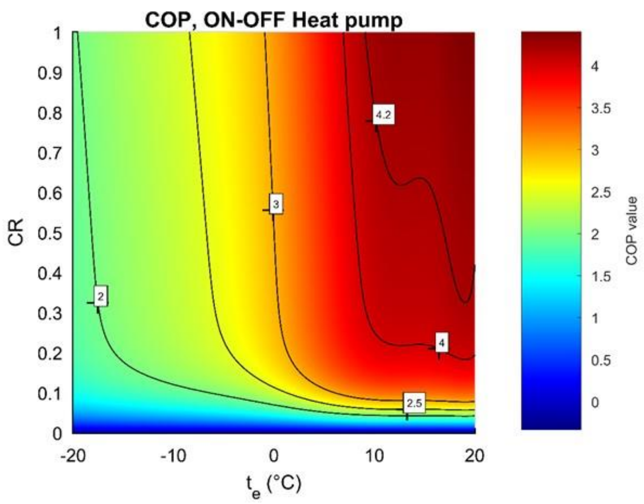

Fig. 2 - *COP* for the on-off HP vs t_e and *CR*

A correct analysis should be carried out considering every hour of the heating season. Indeed, according to UNI/TS 11300-4 the "bin method" will be employed, i.e. measured hourly mean outdoor air temperature values replace the normal distribution of the outdoor air temperature proposed by the same norm. The regulation introduces the concept of "bin hours", defined as the number of hours of the heating season in which there is a t_e included in a defined temperature range called bin, i.e. is a temperature interval of 1K centered on an integer value.
In Table 3 the heating period, the climatic zone, and heating degree days (HDD) according to Italian law DPR 412/1993, are reported for the five Italian mentioned municipalities.

Table 3 – HDD, climatic zone and heating system operational period.

City	Climatic zone	Heating Degree Days	Heating system operational period
Ventimiglia (IM)	C	1119	15 Nov - 31 Mar
Genova (GE)	D	1435	1 Nov - 15 Apr
Bologna (BO)	E	2259	15 Oct - 15 Apr
Milano (MI)	E	2404	15 Oct - 15 Apr
Livigno (SO)	F	4648	365 days

Weather data downloaded from ARPA websites have been revised in relation to the heating period shown in Table 3 to obtain bin hours for every town considered. In Fig. 3, bin hours obtained for Bologna, years 2017, 2018, and 2019 are reported. Bin hours distributions have been obtained for Ventimiglia, Milano and Livigno as well. For example, Fig. 3 shows that, for Bologna, 213 bin hours at 14°C occurred during 2019: it means that for 213 hours during the mentioned heating season, the hourly mean outdoor air temperature was in the range 13.5-14.5°C.

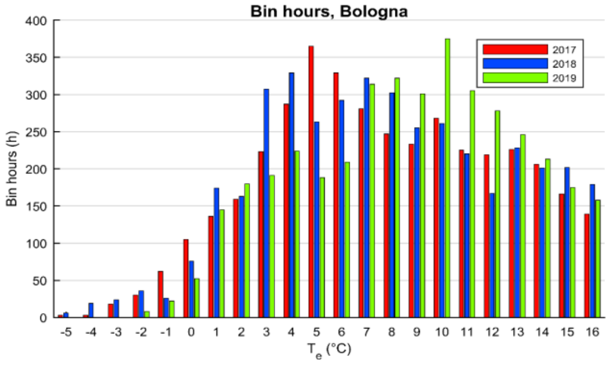

Fig. 3 - Bin hours for Bologna, year 2017, 2018 and 2019.

by employing eqs. (1) and (2) and as a result of the summation of the thermal and electrical energies from the spreadsheet shown in Table 4.

2.2 Influence of heat pump sizing on performances

The correct design and sizing of the heat pump have an important influence on its performance. Usually, the heat pump is sized in order to partially (but not totally) supply the thermal request, especially for on-off HPs. Thereby the machine is sized to work for a long time with a high value of *COP*. The residual part of the thermal request is supplied by an auxiliary generator (in this case auxiliary electrical resistances) that are switched on only whenever the HP is unable to supply the thermal request of the building. In the scenarios of the present analysis, for every considered place there is a value of the power requested by the building to the heating system that

Table 4 – Extract from spreadsheet, scenario: Livigno, inverter HP, year 2019.

t_e	h_b	$P_{th,REQ}$	$Q_{th,REQ}$	$P_{th,max,HP}$	$P_{in.HP}$	COP_{PL}	$Q_{th,HP}$	$Q_{th,BU}$	$EE_{in,HP}$	$EE_{in,BU}$
°C	h	kW	kWh	kW	kW	-	kWh	kWh	kWh	kWh
-5	371	3,00	1113	5,55	0,79	3,78	1109	0	293	0
-4	402	2,86	1149	5,56	0,76	3,76	1149	0	306	0
-3	439	2,71	1192	5,53	0,73	3,72	1194	0	320	0
-2	451	2,57	1160	5,49	0,70	3,69	1164	0	316	0
-1	413	2,43	1003	5,49	0,67	3,64	1008	0	277	0
0	370	2,29	846	5,48	0,63	3,62	844	0	233	0

The behavior of the heat pumps is analyzed by employing spreadsheets, where the main items were:

- Mean hourly outdoor air temperature t_e (°C)
- Number of hours of heating season h_b such that the specific outdoor air temperature is within a fixed range (bin hours)
- Thermal power $P_{th,REQ}$ (kW) and energy $Q_{th,REQ}$ (kWh) requested by the building for the heating system
- Maximum thermal power supplied by heat pump $P_{th,maxmHP}$ (kW)
- Electric power $P_{in,HP}$ (kW), and energy $EE_{in,HP}$ (kWh) to the heat pump
- Energy $EE_{in,BU}$ (kWh) to auxiliary electrical resistances
- *COP*, evaluated by eq. (4)
- Thermal energy output from heat pump $Q_{th,HP}$ (kWh) and thermal energy output from auxiliary electrical resistances $Q_{th,BU}$ (kWh).

In Table 4 there is an extract from the spreadsheet set up for the analysis. Seasonal indexes are calculated

maximizes seasonal index $SCOP_{on}$. For example for Bologna, on-off HP and the year 2017 the maximum value of $SCOP_{on}$ is 3.44 for a heating system (heat pump and auxiliary electric resistances) sized to supply a thermal power requested by the building of 7kW (Fig. 4). In Table 1 the maximum power requested from the building is reported as the value that maximizes $SCOP_{on}$ for the considered town.

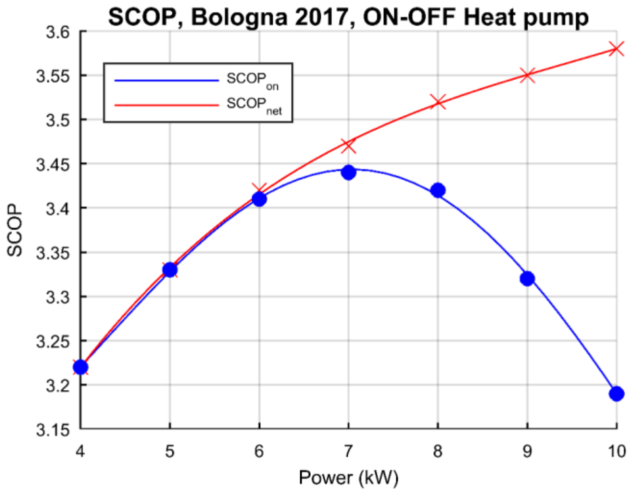

Fig 4 - $SCOP_{on}$ for on-off HP in Bologna.

3 Results

The seasonal indexes are shown in Table 5. As already underlined, with reference to Bologna, Milano and Livigno the analysis covers the years 2017, 2018 and 2019, while for Genova and Ventimiglia it refers to the year 2019.

indexes, showing increasing up to 45% between Livigno and Ventimiglia. The comparison also shows that the variation is more relevant for on-off HP.
Results in Table 5 underline also the influence of heat pump typology on *SCOP*: inverter heat pump better behaves in all the considered scenarios and the maximum increase on seasonal indexes is observed for machines installed in a colder or warmer climate (the increase of $SCOP_{net}$ related to an inverter heat pump for Livigno, Genova and Ventimiglia is at least 20% larger than $SCOP_{net}$ of on-off heat pump). For an intermediate climate (like Bologna, Milano) *SCOP* variations are approximately 10%.
Lastly, analysis is made considering different heating seasons for the same town. Results show that percentage increases (or decreases) of seasonal indexes are lower than the previous comparison showed above (less than 6%). *SCOP* variations are larger for the inverter heat pump instead of on-off heat pump for all places considered in this comparison (Bologna, Milano and Livigno), and the smallest SCOPon and $SCOP_{net}$ variations are observed for Livigno instead of Bologna and Milano: for example for the inverter HP in Milano $SCOP_{on}$ for year 2017 is 3.55 and for year 2019 is 3.85, and that

Table 5 – Seasonal indexes for Bologna, Milano, Livigno (years 2017, 2018, 2019) and for Genova and Ventimiglia (year 2019).

		ON-OFF HP		INVERTER HP	
Place	**Year**	$SCOP_{on}$	$SCOP_{net}$	$SCOP_{on}$	$SCOP_{net}$
Bologna	2017	3.44	3.47	3.87	3.92
Bologna	2018	3.39	3.45	3.81	3.90
Bologna	2019	3.51	3.51	4.00	4.01
Milano	2017	3.27	3.38	3.55	3.72
Milano	2018	3.37	3.42	3.73	3.81
Milano	2019	3.37	3.44	3.74	3.85
Livigno	2017	2.63	2.67	3.30	3.38
Livigno	2018	2.68	2.71	3.36	3.41
Livigno	2019	2.67	2.69	3.36	3.42
Genova	2019	3.77	3.79	4.50	4.56
Ventimiglia	2019	3.86	3.86	4.70	4.71

Table 5 shows that seasonal indexes vary a lot from one place of installation of the heat pump to another. For example, for Livigno $SCOP_{on}$ value is 3.36 and $SCOP_{net}$ 3.42 for inverter heat pump (year 2019); with reference to the same inverter HP, for Ventimiglia $SCOP_{on}$ is 4.70 and $SCOP_{net}$ is 4.71. The air-to-water heat pumps perform better when installed in a warm climate and worse if installed in a cold climate, as expected from the *COP* trend. This comparison shows that the climate of the place where the HP is installed strongly reflects on seasonal

shows an increase on $SCOP_{on}$ of approximatively 8% between year 2017 and 2019. For the same inverter, HP placed in Livigno $SCOP_{on}$ increase is 1.8% between 2017 and 2019.
In conclusion, we found that the climate of the installation place is the most important factor that affects seasonal indexes of HP (*SCOP* variation up to 45%); heat pump type affects *SCOP* with variation up to 27% instead, and finally, also the heating season affects the seasonal performances of the heat pump/heating system, but less than 10%.

4 Conclusion

The performances of electric air-to-water heat pumps have been investigated with reference to the climatic conditions of the installation place. We focused on five different Italian municipalities, and, in order to evaluate the weather conditions, the bin-method proposed by UNI/TS 11300-4 is employed. Two different types of heat pumps (on-off and inverter-driven variable speed compressor) are compared. The analysis shows that

- the climate of the installation place is the most important factor which affects seasonal indexes of HP;
- heat pump type affects *SCOP* as well, and inverter HP better performs than on-off HP;
- also the heating season affects the seasonal performances of the heat pump/heating system, but is less important than the previous ones.

Since important *SCOP* variations occur depending on climatic conditions, also with reference to differently behaving hears considered for heating season, further investigations may expand the number of years for the analysis alongside dynamic simulations [16]. Moreover, further investigations of the present analysis may include the influence of the relative humidity of external air on heat pump performances, as other authors suggest [17].

References:

[1] Thomson W. On the Economy of the heating or cooling of buildings by means of currents of air. *The London, Edinburgh, and Dublin Philosophical Magazine and Journal of Science* 7, 1854
[2] Lowes R, Rosenow J, Qadrdan M, Wuc J. Research and policy principles for heat decarbonisation through smart electrification. *Energy Res Soc Sci* 2020 Dec; 70: 101735.
[3] https://www.energypolicy.columbia.edu/research/report/decarbonizing-space-heating-air-source-heat-pumps
[4] Duicu S. Using the heat pumps as a renewable source of energy *WSEAS Transactions on Design, Construction, Maintenance*, 2022 Volume 2.
[5] Sarbu I, Sebarchievici C. General review of ground-source heat pump systems for heating and cooling of buildings, *Energy and Buildings* 2014; Volume 70, Pages 441-454.
[6] Wang R, Yang C, Ni L, Yao Y. Experimental study on heat transfer of soil with different moisture contents and seepage for ground source heat pump. *Indoor and Built Environment* 2020; Vol. 29(9) 1238–1248.
[7] Jahanbin A, Semprini G, Impiombato NA, Biserni C, Rossi di Schio E. Effects of the Circuit Arrangement on the Thermal Performance of Double U-Tube Ground Heat Exchangers. *Energies* 2020, 13, 3275.
[8] Mouzeviris GA, Papakostas KT. Study on Air-to-Water Heat Pumps Seasonal Performances for Heating in Greece, *Energies* 2022; 15, 279.
[9] Pospíšil J, Spilacek M, Bartu M, Marton D. Seasonal Benefits of Intraday Heat Accumulation in System with Air Source Heat Pump for Central Europe Climate Conditions, *Chemical Engineering Transactions* 2017; 61, 1663-1668.
[10] Rossi di Schio E, Ballerini V. The scop of an air source heat pump: Comparison between on-off and inverter heat pump. *JP Journal of Heat and Mass Transfer* 2021; Volume 24, Issue 1, Pages 79 – 86.
[11] UNI/TS 11300-4, Energy performance of buildings – Part 4: Renewable energy and other generation systems for space heating and domestic hot water production, (2016).
[12] Rossi di Schio E, Ballerini V, Dongellini M, Valdiserri P. Defrosting of air-source heat pumps: Effect of real temperature data on seasonal energy performance for different locations in Italy. *Applied Sciences* 2021; 11, pp. 1 – 15.
[13] https://www.mise.gov.it/index.php/en/incentivi/energia/superbonus-110
[14] Bianco V, Marchitto A, Scarpa F. Heat pumps for buildings heating: Energy, environmental, and economic issues. *Energy & Environment* 2020; 31, pp. 116-129.
[15] EN 14825, Air conditioners, liquid chilling packages and heat pumps, with electrically driven compressors, for space heating and cooling – Testing and rating at part load conditions and calculation of seasonal performance, (2013).
[16] Naldi C, Dongellini M, Morini GL, Zanchini E. Comparison between hourly simulation and bin-method for the seasonal performance evaluation of electric air-source heat pumps for heating, *Building Simulation Applications* 2015 - 2nd IBPSA-Italy Conference, Bolzano
[17] Vocale P, Morini GL, Spiga M. Influence of outdoor air conditions on the air source heat pumps performance, *Energy Procedia* 2014; 45, 653-662