Inverter-Driven Heat Pumps for Space Heating: Comparisons of Air-to-Water and Air-to-Air Units

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Abstract

Among the renewable sources systems for space heating, air-source heat pumps are the most promising technology. The air-source heat pumps European market is dominated by air-to-water and air-to-air heat pumps.

In this study we present a comparative analysis of these two types of machines, in terms of electricity consumption. Buildings (with low and high thermal inertia) and their heating systems were simulated in different European climates. Results show that the thermal inertia of the envelope penalizes the performance of the system and this effect is more pronounced in the A-W system.

Introduction

The aerothermal energy source has been recognized as renewable by the European Directive 2009/28/EC, so that, under certain conditions, a fraction of the thermal energy obtained from an air-source heat pump (ASHP) (depending on the seasonal performance factor - SPF) can be considered renewable and this helps to fulfil the requirements of the Directive itself.

ASHPs have an important role in the residential heating and cooling and they are expected to be dominant in the market, compared to heat pumps with other energy sources (EHPA, 2015). Commercial products have reached a good competitiveness compared to traditional heat production systems and their efficiency has continuously been improved especially in recent years, also because of the adoption of inverter-driven compressors.

The higher efficiency of variable-speed units compared with on/off controlled systems has been acknowledged since long time (Tassou et al., 1983) but only recently these machines are displacing those with fixed capacity in the residential market. The energy saving potential is significant and it is strongly dependent on the climate (Adhikari et al., 2012) and on the load (i.e. building-plant system behaviour).

Among ASHP we can distinguish between air-to-water (A-W) and air-to-air (A-A) heat pumps. According to the European Heat Pump Market and Statistics Report 2015 (EHPA, 2015), the former are the most widespread but the latter represent the fastest growing heat pump segment across Europe. The purpose of this work is to develop a simulation approach to investigate how the seasonal performances of the two types of ASHP are influenced by some factors, such as the climate or the building thermal behaviour. To the authors' knowledge, even if this topic is the subject of much debate, not much research work has been performed about it.

Methods

Simulation

The seasonal behaviour of A-W and A-A units for space heating has been evaluated by means of a dynamic model that includes a building and its heating system. The model was set up in the TRNSYS simulation suite. Standard and TESS libraries are used for many of the system components, whereas new subroutines were developed to simulate the part load operation of the ASHPs, in order to model the behaviour of the latest generation machines.

Building

The building is a well-insulated semi-detached house, presented in Prada et al. (2015), modified to consider the influence of the thermal capacitance of the building envelope: a concrete blocks and a timber envelope were considered, respectively with an internal areal capacity of 50.6 kJ m^{-2} K^{-1} and 36.5 kJ m^{-2} K^{-1}. In both the cases, walls have a thermal transmittance U = 0.29 W $m^{-2}K^{-1}$.

With the A-A heat pump application, the heat is transferred to the building by an air flow, specified as "ventilation" in the building model. In the application with the A-W heat pump, the heat is delivered to the building using water as the heat transfer media and the terminal unit is a radiant floor heating system, modeled as an "active layer" (TRNSYS documentation, 2012).

Weather data

The weather data used for the simulations are the test reference year (TRY) of four European cities: Helsinki (Finland), Berlin (Germany), Milan and Rome (Italy). These climates are classified respectively as 6A, 5C, 4A and 3C, according to the ASHRAE 90.1 classification. From each TRY, a six-months period (October 15th – April 15th) was selected for the simulations.

Heat pump

Two different heating systems were simulated: a) a hydronic system, including a 100 litres buffer storage tank, where the A-W heat pump supplies heated water to underfloor radiant panels and b) an A-A heat pump heating the air supplied to the heated space with a direct expansion coil. The A-W and A-A heat pump TRNSYS Types used for the simulation were modified in order to take into account the part-load performances of inverter-driven machines. The part-load operation is described by a function (Figure 2) that can be considered representative of the last generation HPs. The part load and full load performance data are given as inputs to the HP models and the instantaneous behaviour depends on the outdoor conditions and the actual thermal load.

The algorithms for the A-W and the A-A are similar. Given the supply set temperature T_{set} and the required mass flow $\dot{m}$ of the heated fluid (water or air) the thermal power is calculated as:

$$\dot{Q}_{req} = \dot{m}c_p(T_{set} - T_{return})$$

With cp the specific heat of the air or the water, depending on the case. The maximum thermal load $\dot{Q}_{max}$ is then obtained from the performance files, based on the outdoor and supply temperatures (for the A-W application) or outdoor and return temperatures (for the A-A application). The capacity ratio CR is defined as:

$$CR = \frac{\dot{Q}_{req}}{\dot{Q}_{max}}$$

Depending on the CR, three cases can occur.

If $\mathrm{CR} > 1$ the actual load is higher than the HP capacity and, consequently, it cannot be fully supplied.

1. When $CR_{min} < CR \leq 1$ the part load performance data are applied; the absorbed power is then calculated taking into account the corresponding COP_{PL}.
2. If $CR < CR_{min}$ the minimum thermal power is supplied. This may result in an on/off operation.

The CR_{min} is the minimum capacity ratio that the heat pump can reach; it was set to 0.2.

As the performance of the ASHPs strongly depends on the design size (Bee et al. (2016), Dongellini et al. (2015), Afify (2008)) a standard sizing method has been defined, in order to limit the influence of the design choices on the results. The method consists in selecting the minimum capacity of the heat pump that can ensure the complete coverage of the peak heating load. In other words, during the peak hours of the heating season, the heat pump works at his maximum capacity (CR=1) and for the rest of the time it works at part load conditions (CR<1). That results in different HP sizes for different climates and/or buildings.

Not many manufacturers publish the performance curves of their products. From the few data available, the performance curves for different source and sink temperatures, shown in Figure 1, were obtained as well as the part load performance, shown in Figure 2, that can reasonably be considered representative of the last generation heat pumps. The curves in Figure 1 have been extended to lower and higher temperatures assuming a variation that follows the Carnot efficiency (by keeping the exergetic efficiency equal to the closest given point).

Control and temperature reset

Both the A-W and the A-A system controllers are provided with an outdoor temperature reset (control of the supply temperature based on the outdoor temperature). The control curves (outdoor vs. supply temperatures) are shown in Figure 3. In addition to the temperature reset (based on outdoor temperature), a zone control was modelled. A temperature controller manages the flow of the heating fluid: in the A-W system the controller works with a 1°C proportional band: the output signal varies between 0 and 1 and consequently the mass flow of the water varies between the minimum and the maximum flow (100 kg h^{-1} - 300 kg h^{-1}). For the A-A application a multi-stage fan speed control was modelled with a dead band of 1°C. Three level of air flow (low – medium – high) can be set on the base of the zone temperature and the set temperature (20°C). Moreover, as mentioned before, the heat pump has an on/off control based directly on the temperature of the fluid exiting from the condenser (air or water). The machine is switched on and off when that temperature differs from the set temperature (with a dead band of 2 °C). In addition, in the A-A system, the heat pump is turned off when the indoor fan is not working. In the A-W system this extra control is not necessary, as the heat pump is not directly connected to the floor heating loops. The control system ensures an indoor temperature between 20°C and 23°C, that is within the comfort range defined by the EN 15251:2007.

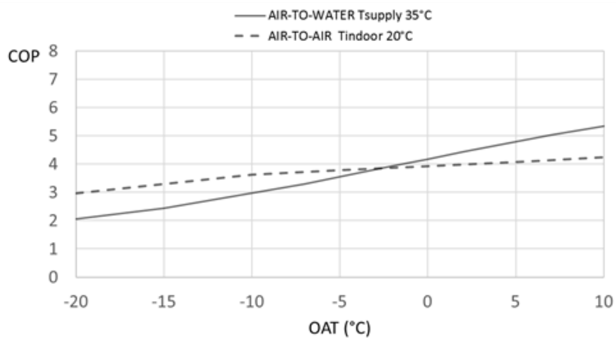

Figure 1: Performance curves as a function of the outdoor ambient temperature Data have been taken from technical datasheets and extended to lower and higher temperatures assuming a variation that follows the Carnot efficiency.

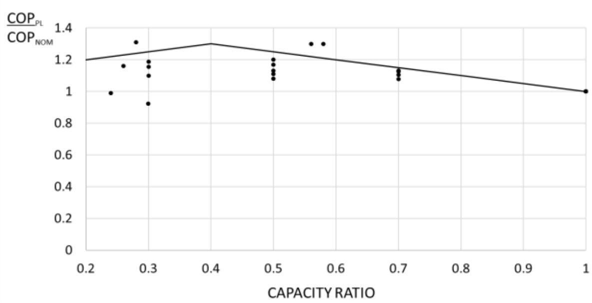

Figure 2: Part load performance for A-A and A-W heat pumps. The dots are not interpolated; they are showed with the purpose to compare the curve used in the simulations and the data of some commercial products.

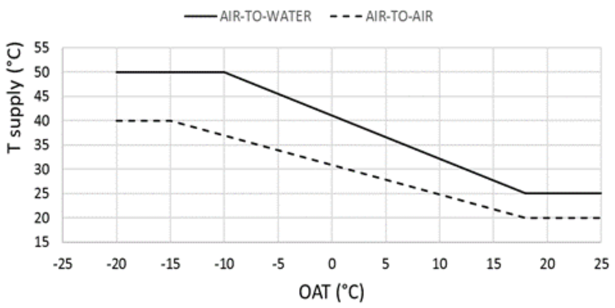

Figure 3: Outdoor temperature reset functions.

Results

Results are presented in terms of electric energy consumption of the heat pumps over the heating season, normalized vs the floor surface (equal to 100 m^2 in all the cases). The pumping power of the A-W heat pump and the indoor fan power of the A-A heat pump have been accounted for.

Energy consumption is always slightly higher for the concrete envelope (especially with the A-W system). As demonstrated by Goia et al. (2015), thermal inertia of the envelope doesn't have a significant impact on the heating needs. Considering the intrinsic HVAC system inertia (higher in the A-W system), the extra inertia of the envelope seems to have a negative impact. Regarding to the difference between the two HP types (water vs. air condensing), there are opposite results for the coldest (Helsinki) and the warmest (Rome) climates. These differences, however, are substantially affected by the performance curves of the machines, about which, few data are still available in the European context, in particular for A-A heat pumps. In fact, although test methods of HPs have been standardized by European Standard (EN 14511:2011-2/3), manufacturer's performance data are in general incomplete and presented in different ways. From the curves shown in Figure 1 is clear that the A-W curve penalizes low outdoor temperatures and favours high temperatures.

Looking at the curves presenting the yearly trends (Figures 5 and 6), it is clear that most of the time the HP operates at part load but this has a positive influence on the COP, because modern heat pumps tend to have a better performance for CR around 40-50% (see Figure 2). In addition, it is noted that the A-W heat pumps are subjected to larger fluctuations of the supply temperature of the heating fluid (water) because of the temperature reset (and, as a consequence, to larger variations of the condensation temperature) with respect to the A-A heat pumps were such fluctuations are substantially smaller and the load variations are accommodated changing the supply air flow rate (i.e. the fan speed).

In warmer climates (Rome), there are periods when the load is so low that the A-A heat pumps is forced to operate outside of its modulation range i.e. in on-off mode. Obviously this effect is less pronounced for the A-W pumps because of the storage tank.

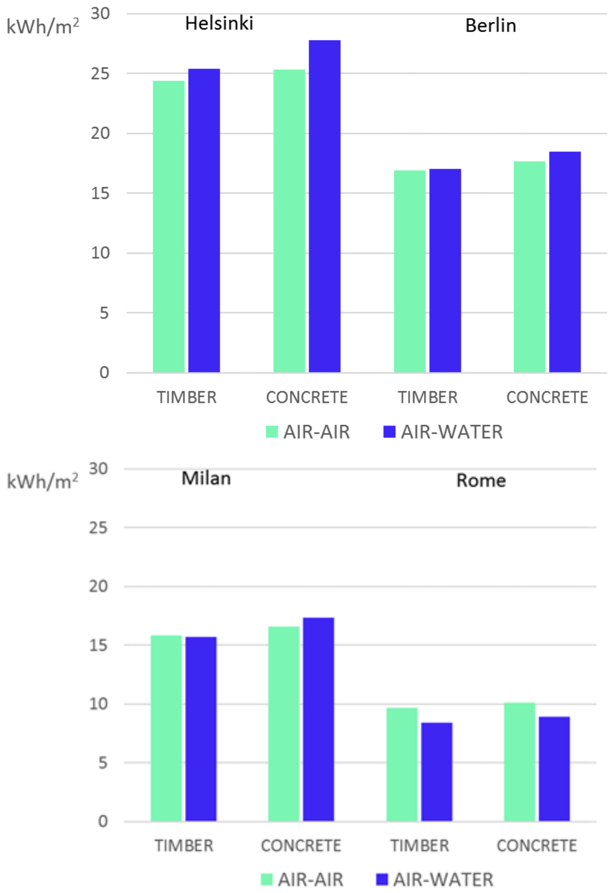

Figure 4: Normalized energy consumption.

Conclusion

In this paper we have shown some preliminary results obtained from 16 simulations with different combination of climates, building envelopes and HP types (air-to-water and air-to-air). From the results we cannot say which system is better in absolute terms. The coldest climate (Helsinki), among the four considered locations, seems to favour the air system, whereas in the case of Rome the water system is favoured by the storage effect. In the intermediate climates (Berlin and Milan) differences in consumption between the systems are not significant. However, the influence of the performance data is strong and, to get reliable results, it is necessary to obtain performance data from other manufactures, either for rated and part load, in order to have more representative performance curves. Further work is currently in progress in order to validate the model with the data that we are collecting from some real systems. Finally, since the seasonal energy needs for these systems are affected by different variables (performance data, size, climate and building type) the sensitivity of the system to those parameters is an aspect to be investigated.

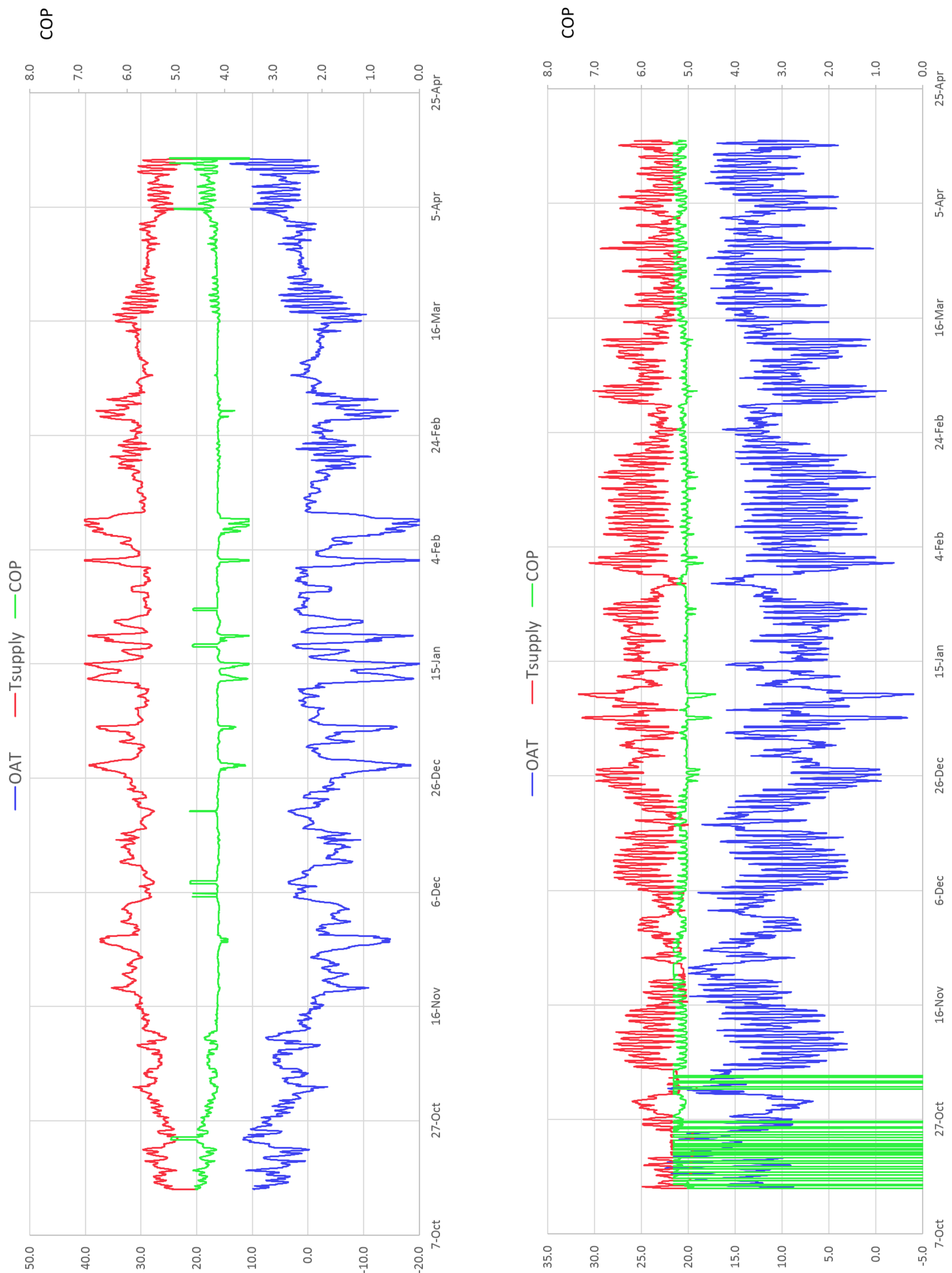

Figure 5: Yearly trends of outdoor ambient temperature, supply temperature and COP for A-A systems in the Helsinki (above) and Rome (below) climates and for the concrete building.

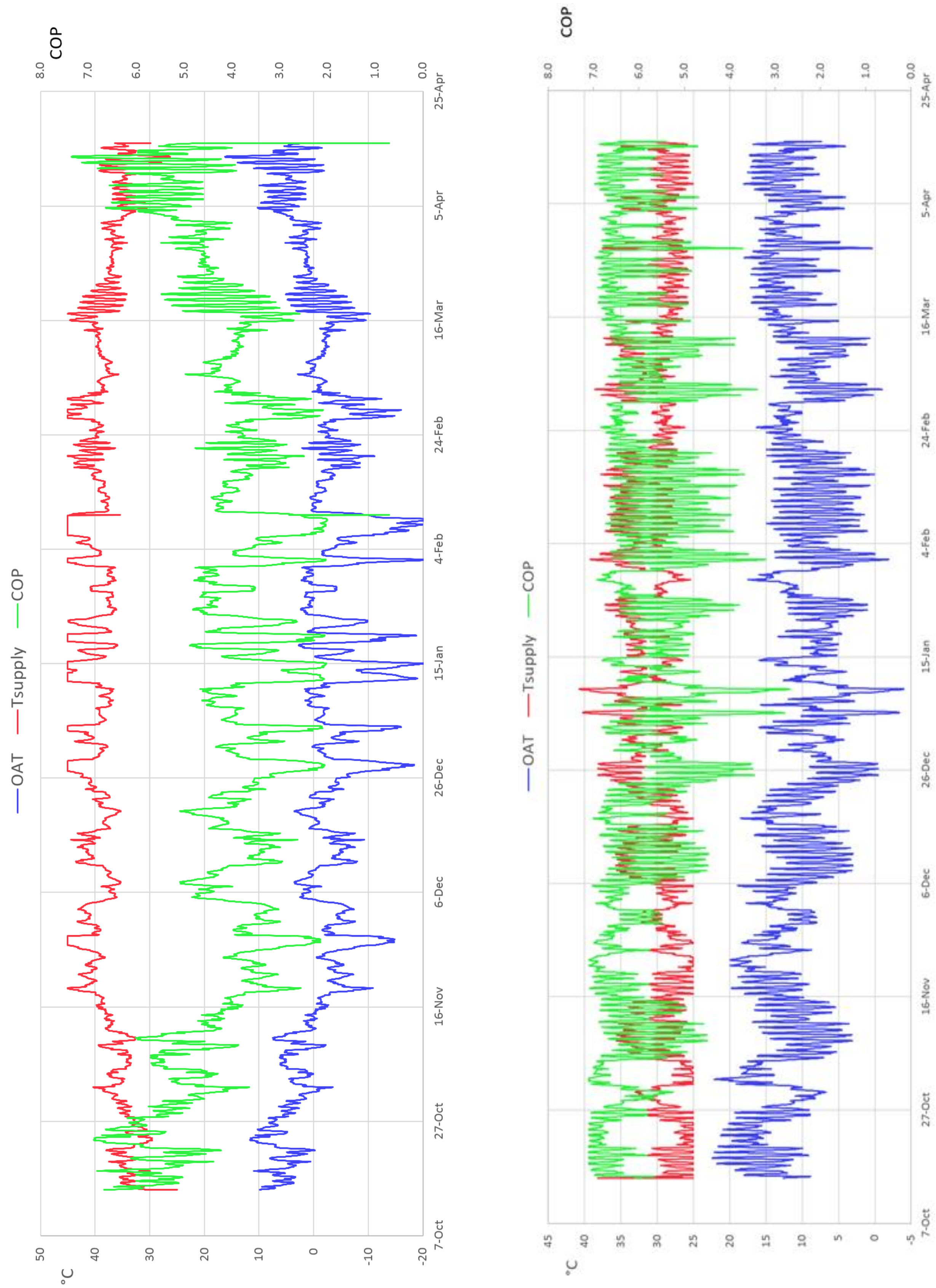

Figure 6: Yearly trends of outdoor ambient temperature, supply temperature and COP for A-W systems in the Helsinki (above) and Rome (below) climates and for the concrete building.

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