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On the Influence of Storage Size and Management on the Consumption of Air Source Heat Pumps in High Performance Buildings

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Abstract

Air-source heat pumps can be coupled with photovoltaic panels, a water storage tank and low temperature hydronic terminals (radiant floor) with the purpose of using renewable sources for domestic heating. Some kind of storage solution is required since the availability of solar energy is most of the time out of sync with the heating needs. In principle the energy storage could take place in water filled storage tanks, acid-lead batteries, and in the building envelope. The thermal capacity of the storage tank depends on the tank size and it could affect the performance of the system. Hence, the system management strategy should consider such inertia in order to correctly control the system, also by taking into account the current availability of solar energy.

This work investigates whether the correct sizing of the water storage tank and its correct management can increase the energy self-consumption and, consequently, the renewable share of the primary energy used. The work analyses the behaviour of such a system configuration during the heating season in different climate conditions. Four European climates and two types of building envelopes, with different thermal capacities (timber and concrete), were considered.

Results show that a control logic oriented to self-consumption can significantly reduce the energy taken from the power grid, with respect to the more typical control systems that reset the supply temperature based on the outdoor temperature. However, increasing the tank size in the range of the typical installations has only a slight effect on the percentage of self-consumed energy. In the case of the control strategy that includes outdoor temperature reset, it was found that this percentage does not change, regardless of the tank size.

1. Introduction

Air-to-water heat pumps have an increasing share in the European heating market. According to the European Heat Pump Market and Statistics Report 2015 (EHPA, 2015), they represent the fastest growing heat pump segment across Europe. The performance of the average commercial products has consistently improved in recent years both at nominal operating conditions and part load conditions, the latter because of the adoption of the inverter-driven compressors.

Moreover, air-source heat pumps (ASHP) will have an important role in order to fulfil the requirements of covering primary energy consumption using renewable energy sources, since the aerothermal energy is considered a renewable source by the Italian Legislative Decree 28/2011 and by the European directive 2009/28/EC. The renewable percentage of energy consumption further increases in the case that a share of the electric input energy comes from a photovoltaic system.

The performance of the heating system depends on many parameters. The thermal inertia of the storage tank (i.e. tank size) could be one of these. Other authors (Arteconi et al., 2013) found that with regard to the established sizing procedures, there is no need for lager storage, except in the case of large PV sizes or highly fluctuating electricity prices. It was also found (Alimohammadisagvand et al., 2016) that with small tank sizes, both the electric consumption and the life cycle cost of the thermal energy storage are lower. However, in literature few works have focused on the increment of the PV self-consumption in high performance buildings.

Moreover, the influence of storage tanks in the performance of heating systems with ASHP has been scarcely investigated in the literature.

This work investigates whether the correct sizing of the water storage tank and its correct management can increase energy self-consumption. The work analyses the behaviour of such a system configuration during the heating season in different climate conditions. Four European climates and two types of building envelopes, with different wall thermal capacitance were considered.

2. Methods

2.1 Simulation Layout

A coupled simulation of the simplified reference building and its heating system was set up in the TRNSYS simulation suite. The reference building is a well-insulated semi-detached house (Fig. 1), presented in Penna et al. (2015). In this work the reference building was modified to consider the influence of the thermal capacitance of the building envelope, consequently, concrete block and 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 cases, the walls have a thermal transmittance of 0.29 W $m^{-2}K^{-1}$, according to the EN ISO 13786 procedure.

The heating system is based on an air-to-water heat pump with a variable speed compressor and coupled with a photovoltaic array. The system is combined with a reference building with radiant floor. The model was set up in the TRNSYS simulation suite (Fig. 2). Standard and TESS libraries are used for many of the system components, whereas a subroutine was adapted to simulate the part load operation of the ASHP, in order to model the behaviour of the latest generation machines (Bee et al., 2016).

The tank model is a stratified liquid storage tank with two inlet and two outlet flows and no internal heat exchangers. The tank is a vertical cylinder and its height was calculated in order to maintain the same shape while varying the volume. The model includes calculation of losses from the tank to the ambient and assumes that all stratification nodes of the tank are uniform in size. The loss coefficient per unit area was set equal to 0.35 $Wm^{-2}K^{-1}$ on the base of the average market product performance.

The part-load operation of the ASHP is described by a function that can be considered representative of the last generation units. The part load and full load performance data are given as inputs to the ASHP model and the instantaneous behaviour depends on the outdoor condition and the required thermal power. The heat pump was sized in order to cover the peak load without auxiliary generators. That results in different HP sizes for different climates and/or buildings.

The radiant floor was modelled with an “active layer” (TRNSYS documentation, 2012). The design specifications are referred to a commercial configuration with 0.12 m pipe spacing and PEX pipes with a diameter of 0.016 m, a thickness of 0.002 m and a thermal conductivity of 0.44 W m^{-1} K^{-1}.

The heating system is powered by either grid or photovoltaic electric power in an “UPS like mode” avoiding battery operation in parallel with the grid. Hence, the system is re-connected to the grid only when the battery has been completely discharged. In the morning, the photovoltaic generated power is used to charge the batteries. As soon as the batteries have been charged, the system uses the residual photovoltaic power, if still available, and then it exploits the stored energy until it is finished. The photovoltaic array is made of 12 modules with an area of 1.6 m^2 each. The total generated energy depends on the radiation input and it changes for the different studied climates.

Four European cities were considered in order to broaden the validity of the results. The simulation code read the weather data for the investigate cities that are 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 15 – April 15) was selected for the simulations.

2.2 Management Approaches

The water supply to the radiant floor is controlled by means of the thermostat signal (setpoint at 20°C, proportional band of 1°C). The flow rate varies linearly between 100 and 400 kg h^{-1}.

Two management approaches were implemented in the simulation layout in order to investigate the possibility to increase the renewable coverage factor during the heating period. The heat pump is controlled setting the desired supply temperature, by means of either:

a. an outdoor temperature reset (OTR) of the supply temperature;
b. a logic that considers a constant supply temperature when the delivered energy comes from the grid whereas a higher temperature when self-produced energy is used (batteries discharging or directly from the panels). That will be called a self-consumption-oriented logic (SCO).

The control system ensures an indoor temperature between 19.5 °C and 23 °C.

2.3 Storage Volumes

Simulations were performed for the four mentioned climates, the two types of envelopes, five tank sizes (in the range of 100 to 1000 litres), and with the two management strategies. The lower storage volumes (up to 500 litres) correspond to the typical tank sizes in residential single unit applications. The range was extended to 1000 litres in order to explore potential benefits from a larger storage, even if those solutions are not easily applicable in practice.

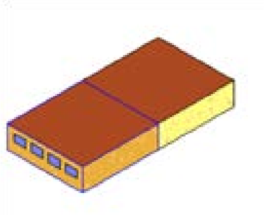


Fig. 1 – Reference building

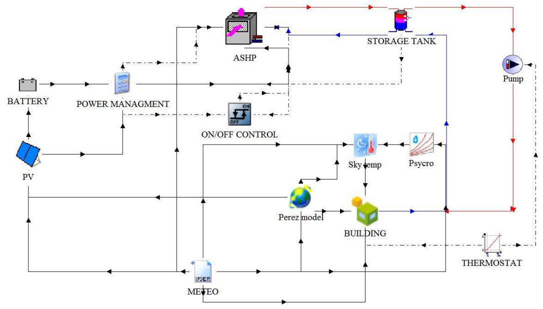


Fig. 2 – Layout of the simulations in TRNSYS Simulation Studio

3. Discussion and Result Analysis

The results of the analyses are the energy consumption of the ASHP and the PV power production use for the heating system. These results are obtained on an hourly basis as shown in Fig. 3.

3.1 Management Approaches

We compared the management approaches, in the cases with a storage volume of 300 litres and 700 litres. The SCO approach increases the self-consumption percentage with regard to the OTR logic, in all the simulations (Fig. 4). With reference to a tank size of 300 litres, the maximum increase is 10 %. That is a consequence of two main facts. First, although the supply temperature range is the same for the two control approaches, with the SCO one the lower supply temperature is more frequent over the season and that results in a more efficient operating condition for longer time (higher COP). Second, the heat pump is turned off (no consumption) for some hours over the season, with a frequency that does not depend on the time of the day or the outdoor temperature (as shown in Fig. 3), but it is rather linked to the radiation and the batteries capacitance. It is necessary to point out that the mentioned increase of self-consumption percentage means, simultaneously, a reduction of total energy needs and an increase of the self-produced share.

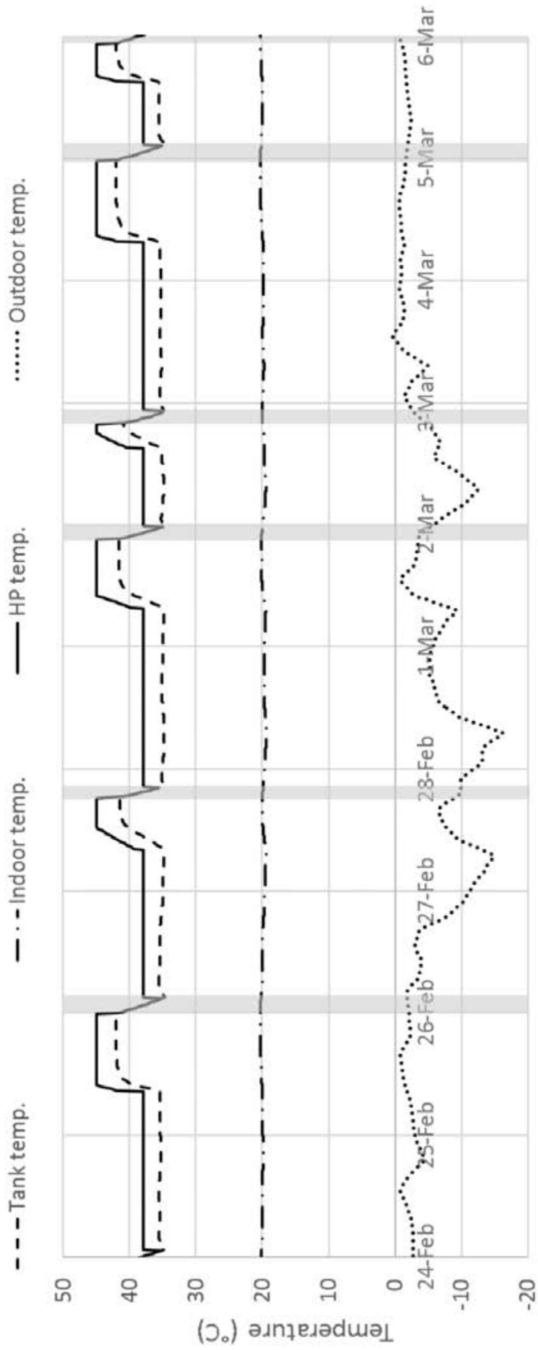
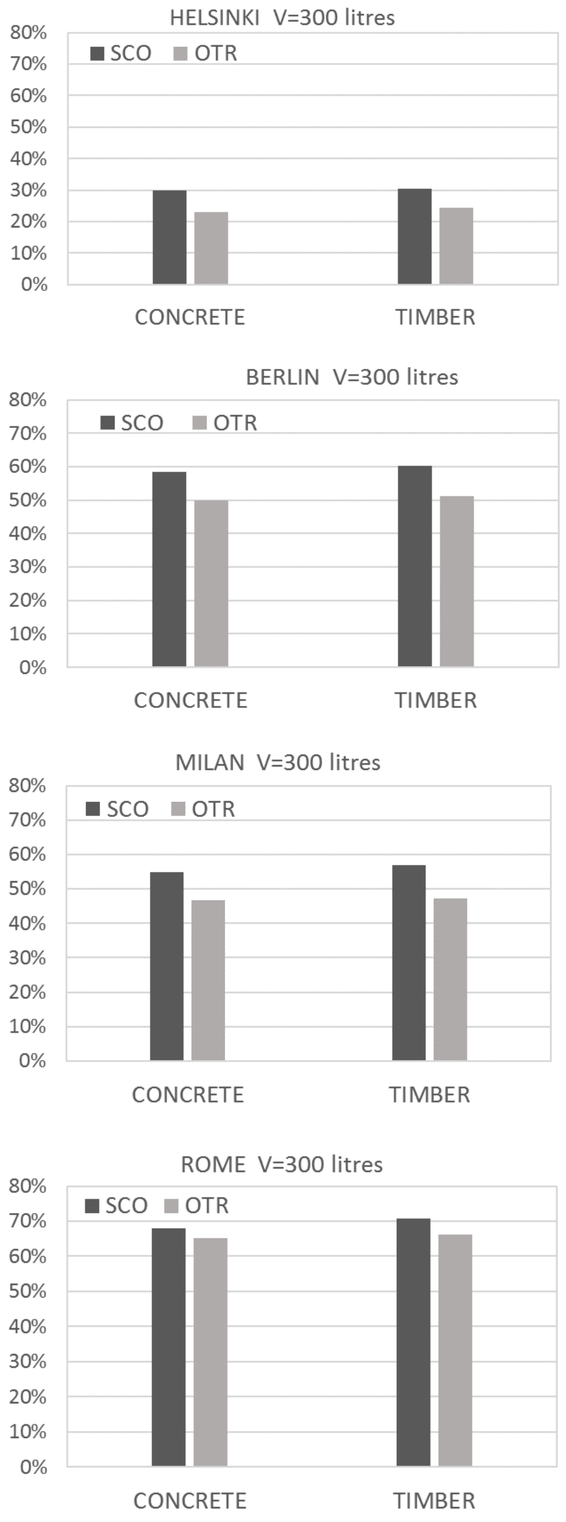


Fig. 3 – Sample of a simulation with the climate of Helsinki and the concrete envelope. The figure is intended to show the behaviour of the system (heat pump and tank) with the SCO management. The shaded areas correspond to the stages in which the HP is off: in these hours the HP supply temperature overlaps the tank temperature (no thermal power is transferred to the water). In the preceding hours the stored water has been overheated using the self-produced energy



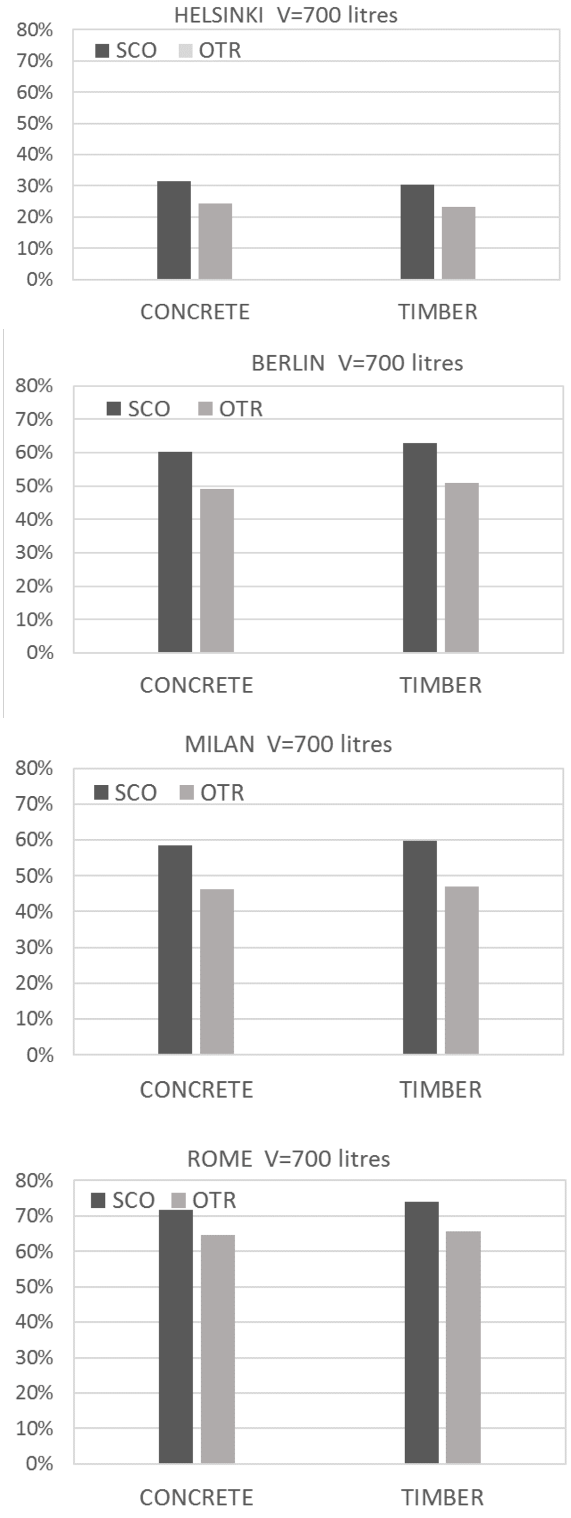


Fig. 4 – Comparisons in terms of self-consumption percentage between the two management approaches: the self-consumption oriented logic (SCO) and the outdoor temperature reset (OTR); results presented with the tank volume equal to 300 litres e 700 litres, for the four climates and the two envelope types

3.2 Storage Volume

The second aspect we analysed is the impact of the storage volume. We found that it does not have any impact on the OTR logic (as can be deducted by comparing the graphs for 300 litres and 700 litres in Fig. 4) and only a moderate impact with the SCO logic. For this second case, results are shown in Fig. 5. The differences reach a 9 % (maximum) increase between 100 and 1000 litres, but only 3 % between 100 and 500 litres, which is a more likely range for the typical residential installations. Here, the increase of the self-consumption percentage is the net effect of a slight increase of total energy needs (1 % for Helsinki, 2 % for Berlin and Milan, and 3 % for Rome) as shown in Fig. 6, and a great increase of the self-produced energy (up to 15 % for the climate of Rome).

Finally, it is interesting to notice some differences between the timber and the concrete envelopes, in average, the systems with a timber envelope seem to take greater advantage from the increase of the tank size (Fig. 5). That is to be expected, since the wooden ones have a lower thermal capacity.

4. Conclusions

This paper is a simulation work on the influence of the storage size and management in air-source heat pump systems for residential space heating, integrated with a photovoltaic array. We compared two management approaches and results show that a very simple logic oriented to self-consumption can significantly reduce the use of energy from the grid. Regarding the tank size, we found that, among the investigated cases, a 500-litre tank allows a maximum of 3 % increase of self-consumption share with respect to a 100-litre tank, and that gain also includes a slight increase of the total consumption. Hence, increasing the storage size does not lead to significant benefits in terms of energy saving.

The findings of this study will be further investigated, in particular the system will be integrated with a more sophisticated management strategy that may include a scheduled working rate of the system, also depending on the occupants' behaviour. By means of an optimization we will also analyse the effect of some parameters such as the heat pump characteristics or the PV and battery sizes.

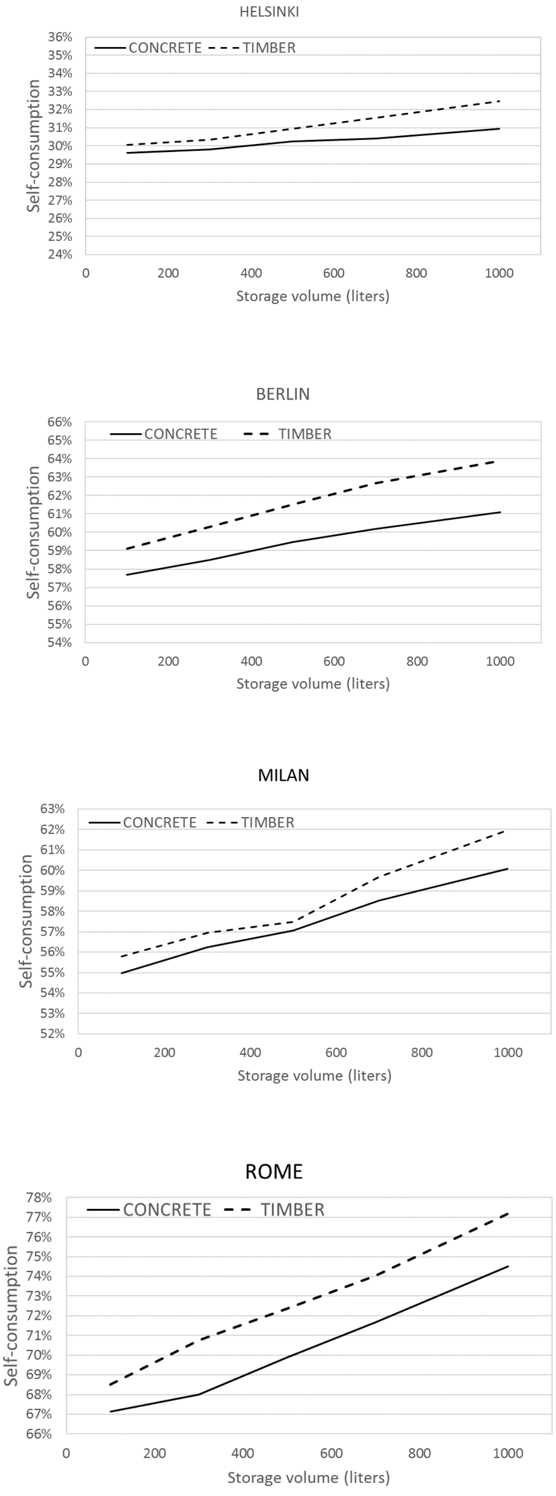


Fig. 5 – Variation of the self-consumption percentage as a function of the storage tank size (volume) for the timber and concrete envelopes and with the SCO strategy

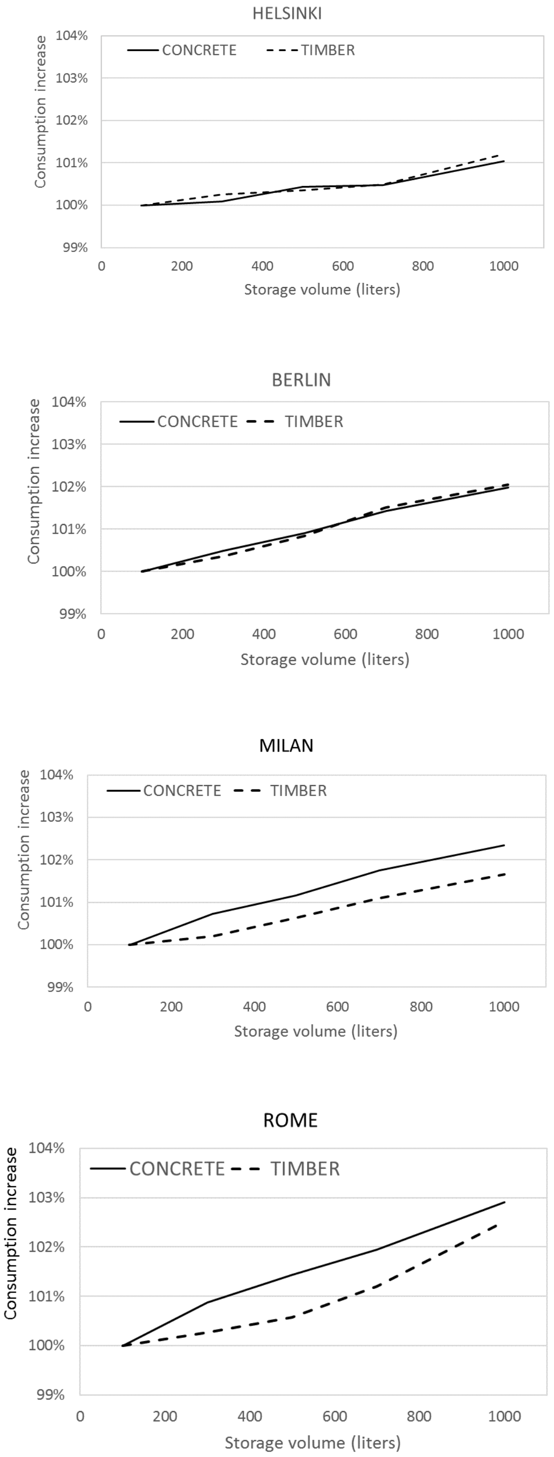


Fig. 6 – Variation of the consumption as a function of the storage tank size (volume) normalized on the case with the lower storage volume (100 litres). Simulations with the SCO strategy

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