DOUBLE SERVICE AIR-TO-WATER HEAT PUMP PERFORMANCES: HOW DO CONTROL PARAMETERS INFLUENCE ELECTRICITY CONSUMPTION AND THERMAL COMFORT?

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ABSTRACT

In Europe, the increasingly restricting environmental regulations push the residential building sector to replace pollutant fossil fuel boilers with more environmentally friendly technologies. Double service Air-to-Water-Heat-Pumps (AWHP) are suitable for this purpose as they can assure space heating (SH) and domestic hot water (DHW) generation while reducing CO_2 emissions. However, AWHP performances are quite dependent of the commissioning and running processes. In this context, this document evaluates the potential impact of the commissioning phase for a double service AWHP in terms of electricity consumption, thermal comfort and energy bill. This evaluation is realized through the study of key parameters settings. The analysis builds upon an AWHP system model developed in the Modelica environment. The results of this work show that commissioning phase has an important influence on system performances. A parameterization adapted to the dwelling is needed in order to guarantee a good SPF (Seasonal Performance Factor), a correct operation as well as user's comfort.

INTRODUCTION

Following the european restricting environmental regulations (García Casals, 2006) Air to Water Heat Pumps are environmentally friendly technologies suitable for retrofit by replacing pollutant fossil fuel boilers. Indeed, they can assure space heating and domestic hot water generation while reducing CO_2 emissions. However, AWHP performances are quite dependent of the commissioning and running processes (Vieira, et al., 2015). For instance, setting inadequate parameters at the time of installation may disturb the heat pump's adaptation to the dwelling and generate overconsumption and thermal discomfort. Besides, this kind of systems requires a large number of parameters (over 50 in average) to be set during the installation of the system (Tejeda, et al., 2014). Commissioning becomes a long and complex phase for the installer, increasing the risk of setting parameter values that are not adapted to the dwelling. Literature shows some examples of key parameters that greatly influence the AWHP behaviour. As studied by Park, et al., 2010 and Hoogmartens & Helsen, 2011, outlet water temperature of a heating system directly affects energy consumption and thermal comfort in the building. Huchtemann, et al., 2013, have also discussed this, proposing an adaptive supply temperature control. Concerning DHW, RAGE report (RAGE, 2014) states that DHW production scheduled in fixed run times impacts on thermal comfort as space heating is off during these cycles. Finally, as stated by Green, 2012 and Green & Knowles, 2011, the choice between indoor air control by air thermostat or by thermostatic radiator valves influences on thermal comfort, on the heating system energy consumption and on the compressor number of cycles. However, no study has ever evaluated the consequences of these key parameters settings, individually and together, in relation to global performances and user's comfort in a dwelling for both space heating and DHW production.The objective of this paper is to evaluate this impact.

The study deals with energy consumption, energy costs and thermal comfort (for both Domestic Hot Water and Space Heating) as functions of the parameters set at the time of commissioning.

Modelling and simulation are done using the object-orientated language Modelica, using the EDF R&D BuildSysPro library (Plessis, et al., 2014). A sensitivity analysis is carried out. The parameters of this analysis which directly affect the AWHP operation are identified and varied. Electricity consumption of each component as well as DHW and indoor thermal comfort are analyzed. The impact of different parameters on peak power demand and on the electricity bill is also computed.

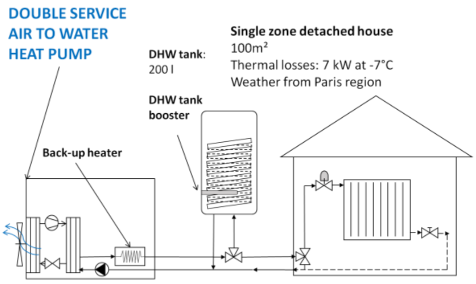

Figure 1: Model description scheme

SIMULATION DESCRIPTION

The model is constituted by different elementary models (cf. figure 1): AWHP, control algorithm, DHW tank, radiators and a single zone detached house.

Model description

More precisely, three models are used. An AWHP (equipped with an electric back-up heater downstream the condenser). A 200 litres DHW tank (equipped with a coil and an electric booster heater). A single zone 100m² detached house (equipped with a hydronic network with a single radiator, whose mass flow rate can be controlled by a thermostatic radiator valve (Slavu, et al., 2007)). The building model is based on a typology of French buildings and is called Mozart (Riederer, et al., 2009). The AWHP is connected to the tank and to the hydronic network thanks to a three-way valve, which sends the hot water either to the immersed heat exchanger in the tank or to the hydronic heating system. No simultaneous operation is allowed (cf. figure1).

Weather data from the region of Paris (France) is used for the simulation of the building model, climate type "Cfb" (Köppen classification). Annual energy consumption amounts to 170 kWh/m^2 for both space heating and DHW generation.

This models assembly is used to simulate and evaluate energy consumption, energy costs and thermal comfort (for both DHW and SH) as functions of the parameters set at the time of commissioning.

Parametric study

A first analysis consisted in identifying parameters that have a key action on AWHP behaviour, on performances and on thermal comfort. These parameters are:

- heating curve (a feed-forward control with the ambient temperature as input (Thomas, et al., 2005)), which can produce an overconsumption up to 18% itself;
- electric backup heaters power (both Space Heating heater and Domestic Hot Water tank booster) which can produce an overconsumption up to 6% and 4%, respectively;
- indoor air thermostat activation, if it is not activated it can increase consumption up to 17% itself;
- run time for DHW or SH generation, settings which can influence up to 3% and 4% on electricity consumption, respectively.

The combination of influences mentionned above are not linear. Indeed, the results of this paper will show that the worse combination of parameters could produce an overconsumption up to 24%.

Table 1 specifies the parameter values used for the annual simulations. All the parameter values can be varied for the same AWHP. Simulations have been realised for each possible combination of parameters. From the results, this document compares the thermal comfort level inside the dwelling, the DHW availability at 40°C, the electricity consumption of each component and the related energy bill of these consumptions.

Besides, in order to evaluate also an inappopriated AWHP nominal power sizing[1], two nominal power values have been chosen: 9 and 12 kW (standard full load heating capacity as defined in (CEN, 2013)).

Table 1: AWHP parameters modified for the study

AWHP parameter	***Values***				***Units***
Electric backup heater power (space heating)	0 / 3 / 6				kW
Electric booster heater power (DHW tank)	0 / 3				kW
Indoor thermostat activation	Yes / No				-
Heating curve Water temp = f(Outdoor air temperature)	Very high	High	Medium	Low	
Water outlet temperature at -7 °C outdoor	55	55	55	55	°C
Water outlet temperature at 0 °C outdoor	55	55	52	47	°C
Water outlet temperature at 15 °C outdoor	40	30	40	30	°C
Run time					
Domestic Hot Water	30 / 60				min
Space heating	30 / 60 / 300 / 600				min

RESULTS AND ANALYSIS

The best configuration of parameters is supposed to assure a trade-off between energy consumption and a reasonable thermal comfort and DHW availability. Therefore, results of the study are analysed taking into account both heating and DHW comfort.

Indoor thermal comfort assessment

Simulations have been carried out on an annual basis and the heating season lasts from the 1st October until the 15th May. During this period, the AWHP produces both space heating and domestic hot water, and it is only during this period when thermal comfort is evaluated. During the non-heating season, only DHW is produced.

Indoor thermal discomfort is expressed as the total annual number of hours when indoor air temperature falls under a given limit. The lower temperature threshold is the indoor setpoint minus 2 °C (in our case 17°C).

Figures 2 and 3 show the comparison between comfort levels and total energy consumption (energy consumption for SH and DHW expressed in annual kWh/m²). Each point in the figures corresponds to a simulation scenario (combination of parameters). Figure 2 shows the results for the 9 kW nominal power AWHP and figure 3 for the 12 kW AWHP.

The results issued from the same heating curve are represented with the same colour and mark. The remaining parameters are not differentiated in order to make the graphic easy to read. Before analysing the figures, we have to keep in mind that a double service AWHP can assure space heating and DHW, but not simultaneously.

Therefore, when DHW load is active, the indoor air temperature in the room falls down. At the end of the DHW load, AWHP then faces a lowered indoor temperature which makes it more difficult to reach the indoor temperature set point. The available heating power at that time is crucial to space heating comfort.

From figures 2 and 3 it can be observed that comfort levels are usually better for the 12 kW AWHP than for the one of 9 kW (thanks to the higher thermal power available in the case of the 12 kW AWHP). However, some parameters combinations for the 9 kW AWHP give a better comfort level than the one obtained by simulating the 12kW AWHP. For instance, some simulations representing *low and medium heating curves* with the 9 kW size give better results than the *high and very high heating curves* with the 12 kW AWHP. The explanation leans on the configuration of the rest of the parameters: electric backup heaters management, indoor air thermostat activation and run times for SH and DHW production.

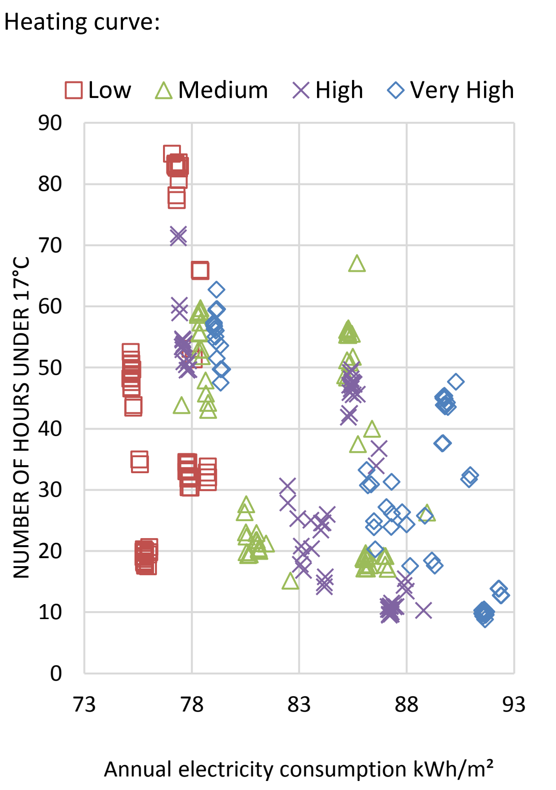

Figure 2: 9 kW AWHP simulation results: Annual energy consumption vs. Comfort levels

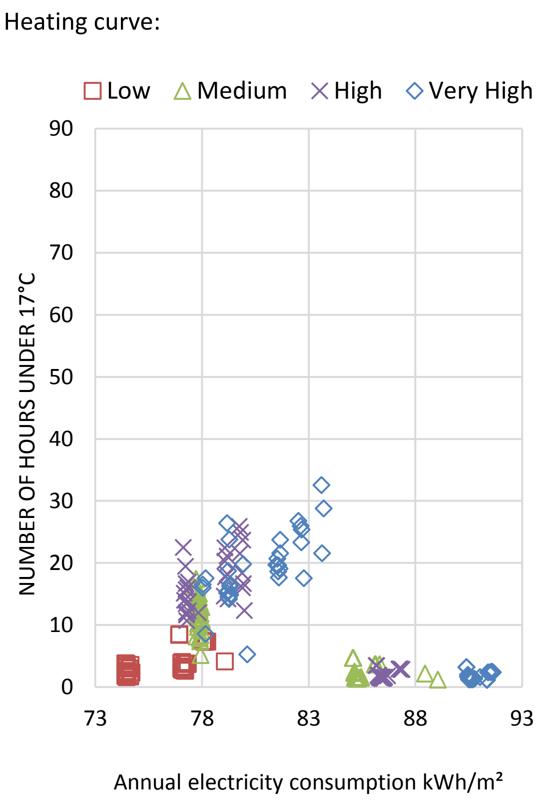

Figure 3: 12 kW AWHP simulation results: Annual energy consumption vs. Comfort levels

If an indoor thermostat is activated, indoor air temperature values are sent to the heat pump in order to modify SH/DHW run times. So when indoor air temperature rises above the set point, the AWHP understands that the space heating load came to zero, and thus the AWHP can switch to DHW generation without waiting the next DHW run time.

On the other hand, without thermostat, run times are fixed at commissioning phase. It could be thought that indoor air comfort will be assured if a long run time for space heating is set. However, it means that DHW tank temperature can drop significantly during this period, resulting in DHW availability problems. Then, when the AWHP switches to DHW it needs more time to heat up the tank. At the same time space heating is off and comfort levels can be degraded. Finally, once the DHW run time is over, the AWHP will have to rise indoor air temperature to the set point starting from a lower level, consuming more power.

These situations can be improved if the electric heater and booster are activated, though reducing the system performances.

Hence, long run times for SH and DHW create big temperature differences (for indoor air temperature and for the water temperature inside the tank) and increase electricity consumptions.

We can state then that the combination of the parameters mentioned above affects directly both the indoor thermal comfort and the energy consumption.

DHW availability assessment

We consider that the non-respect of domestic hot water availability is produced when tap water falls under 40°C. In order to compare simulation results, the number of hours when DHW temperature falls under 40°C is calculated.

Both AWHP nominal powers can assure DHW availability above 40°C when one of the following options is chosen:

- electric booster tank heater is connected,
- run time for SH and DHW are adapted to the dwelling thermal behaviour and to the users' behaviours.

The worst results show unavailability of maximum 2.5 hours per year.

Actually, when the SH-DHW management parameters are optimized, DHW can be fully generated by the heat pump (no backup required) and indoor thermal comfort may remain acceptable.

We can find this case for the 12 kW AWHP and the following parameters configuration: *low heating curve, 30 minutes for DHW tank load, 30 minutes for SH load and indoor thermostat connected.*

Electricity consumption analysis

The electricity consumption of the system is linked to the water temperature set point. Therefore, a brief description of controls is required before any analysis.

To heat up the DHW tank, the AWHP generates hot water at its highest output temperature. To reduce heating up duration or substitute the heat pump, an electrical booster heater can operate as well.

For space heating, there are broadly two control layers for keeping indoor air temperature to set point.

First, controls fix the outlet water temperature set point to meet building thermal losses as a function of outdoor air temperature (given by the heating curve). This is assured either by the AWHP, by the backup heater or by both at the same time.

Secondly, the indoor air temperature is controlled either by thermostatic radiator valves (TRV) or by an indoor air thermostat. TRV adjusts the radiator water mass flow rate to keep air temperature to the set point. The indoor thermostat sends the indoor air temperature value to the heat pump. Then the AWHP modifies controls in consequence (by switching to DHW if needed or by switching off all the system if no heating or DHW is needed).

When TRV are used and there is no information about indoor air temperature, the water pump of the hydraulic network must run permanently. This is because the AWHP needs the return water temperature in order to carry out control.

We can see in figures 2 and 3 that electricity consumption varies greatly: between 92 kWh/m² and 74 kWh/m² per year, i.e. a 20% reduction between different parameter configurations. This variation is mainly due to the following reasons:

- the electricity consumption depends on the chosen heating curve. Indeed the compressor electricity consumption is proportional to the difference between outlet water temperature and outdoor air temperature. For the same heat provided, the higher the heating curve, the higher the system consumption. This appears clearly in both figures (2 and 3). *Very high heating curve* leads to higher consumptions than *low heating curve.*
- If the thermostat is not connected (the rest of parameters are considered unmodified), the electricity consumption increases. This is because the auxiliary devices (water pump and electronics) are always on. This can be observed in both figures 2 and 3 if we look at the results with the same heating curve configuration, similar comfort levels but with different electricity consumption.

- The non-optimal choice of parameters may generate over consumptions due to the use of electric backup heaters. A wrong choice of the heating curve and the DHW/SH production run times may lead to big differences between water outlet temperature and the set point. In order to reduce this temperature difference, the AWHP runs the backup heater downstream the condenser, increasing the electricity consumed.

Disaggregated electricity consumption

In order to better illustrate how the global electricity consumption is affected by each component of the system, we have analysed their consumptions separately: the heat pump (compressor and electronics), the water pump and the backup heaters (downstream the condenser and immerged in the DHW tank). Figure 4 illustrates the total consumption (space heating and DHW generation) for both AWHP nominal powers (9 and 12 kW).

As the heating curve and the use of the indoor air thermostat have shown to be the most influencing parameters on electricity consumption, the comparison is made by varying these parameters. Indoor air control is done by thermostatic radiator valves "*TRV*" or by an indoor thermostat "*TH*". Therefore, the results shown in figure 4 are the average for the rest of parameters configurations (SH/DHW management and backups heater and booster).

The consumption results are averaged from the parameters configurations that ensure less than 24 hours/year discomfort conditions. There is no result for the 9 kW AWHP with a "low" heating curve configuration and TRV as the indoor air temperature control at these configurations do not meet this comfort criteria.

Results analysis are:

- The electricity consumption of the worst parameter configuration (92 kWh/m²) is 24% higher than the best configuration (74 kWh/m²);
- Within the same comfort zone (< 24 hours / year), annual electricity consumption is higher for the 9 kW AWHP (SPF degradation related to the use of electric backup heaters);

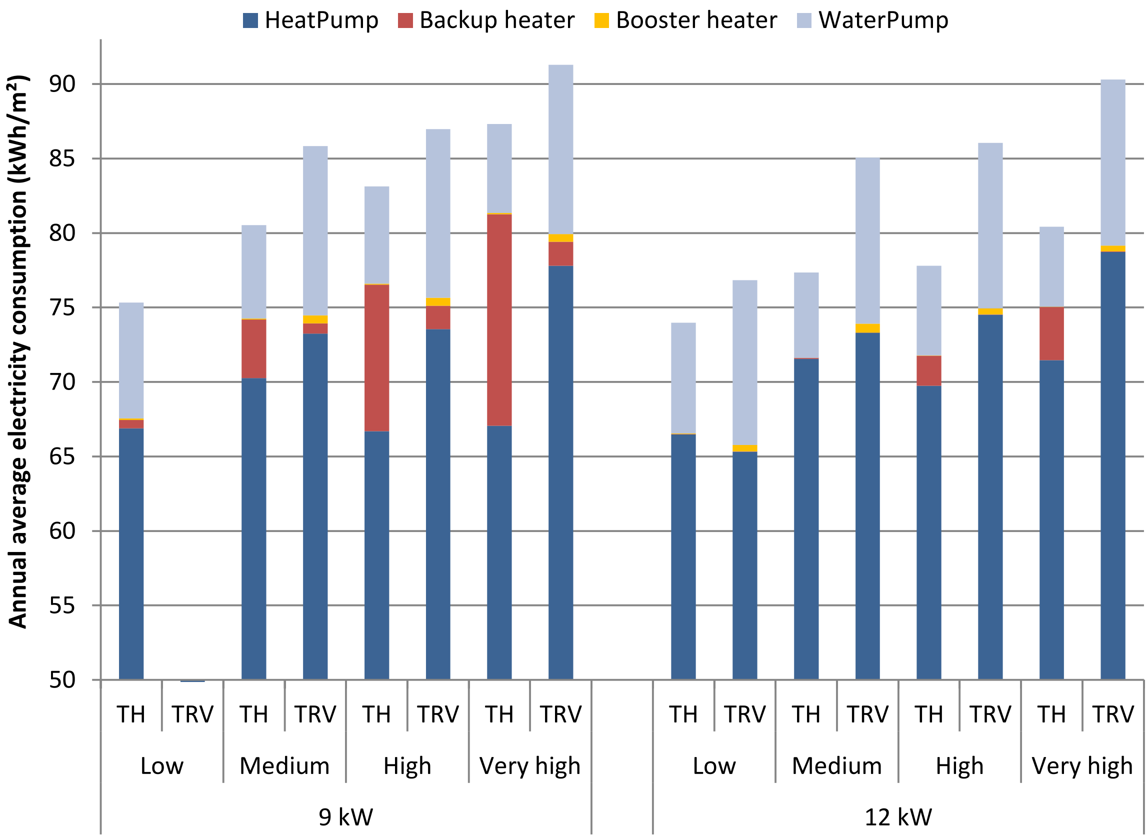

Figure 4: Annual average electricity consumption analysed by component

Heating curve is called "low", "medium", "high" and "very high". "TRV"means thermostatic radiator valves and "TH" indoor thermostat.

- For the electric backup heater (downstream the condenser), the coverage rate is higher for the 9 kW AWHP (as the thermal power of the AWHP is not enough to meet thermal needs);
- For the electric backup booster (immerged in the tank), the coverage rate is higher when the thermostat is not used (the heat pump has less information available to manage properly the DHW generation);
- Consumptions are directly affected by the chosen heating curve;
- The water pump consumption is higher when thermostat is not used (as it runs continuously).

Seasonal Performance Factor (SPF)

In order to analyse the system performance, this paper uses the Seasonal Performance Factor following the guidance of the SEPEMO report (Nordman, et al., 2012). This document proposes different seasonal performance factors taking into account several boundaries of the system (thermodynamic cycle, auxiliary pumps, electric backups heaters...).

We can define then:

$$\mathrm{SPF_{H1}} = \frac{\text{Heat Provided (Heat Pump)}}{\text{Electricy (Heat Pump)}} \quad (1)$$

$$\mathrm{SPF_{H2}} = \frac{\text{Heat Provided (Heat Pump)}}{\text{Electricy (Heat Pump+heat source pump)}} \quad (2)$$

$$\mathrm{SPF_{H3}} = \frac{\text{Heat Provided (HP+electric backups)}}{\text{El(Heat Pump+h.source pump+backup)}} \quad (3)$$

$$\mathrm{SPF_{H4}} = \frac{\text{Heat Provided (HP+electric backups)}}{\text{El (HP+h.s.pump+backup+h.sink pump)}} \quad (4)$$

Heat source pumps are the pumps used by the geothermal heat pumps or the fans used by the air-to-water and air-to-air heat pumps. Heat sink pumps are the water pumps or the fans placed inside the building for heat distribution. $\mathrm{SPF_{H1}}$ and $\mathrm{SPF_{H2}}$ are the same in our study as the heat source pump (fan) is integrated in the heat pump consumption.

Table 2 shows the Seasonal Performance Factors of the simulations previously presented in figure 4. Best global performance (*SPF_{H4} =2.51*) is achieved by the 12 kW AWHP with a *low heating curve* configuration and an indoor air *thermostat* control.

However, for the same AWHP power and heating curve configuration, looking at the performance factors which do not take into account the water pump consumption, the configuration with TRV is better (*SPF_{H2} = 2.89 and SPF_{H3}= 2.88*).

Table 2: SPF for different parameters settings

Nom. power	***Heating curve***	***Indoor air control***	SPF_{H2}	SPF_{H3}	SPF_{H4}
9	Low	TH	2.77	2.75	2.47
		TRV	-	-	-
	Medium	TH	2.56	2.48	2.29
		TRV	2.67	2.65	2.30
	High	TH	2.60	2.39	2.20
		TRV	2.63	2.59	2.25
	Very high	TH	2.56	2.29	2.13
		TRV	2.54	2.50	2.19
12	Low	TH	2.80	2.79	**2.51**
		TRV	**2.89**	**2.88**	2.46
	Medium	TH	2.55	2.54	2.36
		TRV	2.69	2.68	2.33
	High	TH	2.58	2.53	2.34
		TRV	2.63	2.62	2.28
	Very high	TH	2.53	2.49	2.32
		TRV	2.55	2.54	2.22

The explanation is that, when a thermostat is used, the AWHP switches the system off when heating is not needed.

During this time, water temperature inside the hydraulic networks falls down. When the system switches on again, the AWHP has to overcome high water temperature differences between the outlet and the set point (switching on the backup heater), reducing the system performance. On the other hand, with TRV the water pump runs continuously and the AWHP does not have to face this high temperature differences, but the total electricity consumption of the water pump reduces global performance.

This study has not used a model of high energy efficiency water pump. If it had, the best system performances would also be achieved with thermostatic radiator valves and not only with an indoor thermostat.

Economic Analysis

We analyse here the consequences in terms of energy bill. For these calculations, we have used the electricity prices on table 3.

In average, the lowest energy bills appear with the *low heating curve and thermostat control* configurations (990 € for the AWHP of 9 kW and 971 € for 12 kW, no tariff subscription costs are included). On the other hand, the highest energy bills are for the configurations with *very high heating curve and no thermostat control* (1194 € for 9 kW AWHP and 1189 € for 12 kW).

The gains in terms of energy bill can rise up to 204 €/year or 218 €/year (for 9 and 12 kW AWHP respectively) for the best parameterization.

If we also take into account comfort, the best trade-off between comfort and energy bill is given by the 12 kW AWHP with the following configuration:

- no electric backup heater,
- booster heater inside the DHW tank,
- low heating curve,
- thermostat control,
- max load duration of 30 min for DHW generation, (SH generation determined by thermostat information)

With this configuration, the comfort levels would be quite acceptable (lack of comfort < 5 hours / year). The energy bill would be around 970 € / year. And the maximum power peaks of the system will not be higher than 7 kW (a maximum peak power of 4 kW for the heat pump and a 3 kW peak power for the booster heater, there is no backup heater).

As tariff subscription price depends on the maximum peak power demanded by the dwelling, the lower the power demand by the AWHP system are, the cheaper the subscription costs.

Therefore, although a 9 kW AWHP can satisfy SH and DHW production (using sporadically the electric backups), in terms of energy bill and grid stability, it is highly recommended to use a 12 kW AWHP without electrical backup heaters. Nonetheless, investment costs increase with the AWHP nominal power.

Table 3: Electricity prices

Electric tariff	***Values***	***Units***
Peak hours	0.151	€/kWh
Off peak hours	0.1044	€/kWh

CONCLUSIONS

This paper has shown the influence of the setting parameters of an AWHP in terms of comfort, energy consumption and energy bill.

Having analysed the impact of the heating curve, backup heaters connection and DHW and space heating priority management, we can conclude that:

1. In terms of comfort:
   - An adapted heating curve to the building performs the best trade-off between energy consumption and comfort levels. The heating curve is the most important control parameter.
   - Comfort is drastically affected by the parameters managing the SH and DHW switch. An adapted run time for SH and DHW may assure comfort for both functions. To that purpose, the installation of an indoor thermostat may help to adapt duration load to users' needs.
   - After comparing two AWHP with nominal powers of 9 and 12 kW in a building with 7 kW nominal thermal losses, it has been shown that the AWHP of 9 kW (assisted by electrical backups (*booster* and *heater* defined in this paper)) gives poorer comfort levels than an AWHP of 12 kW without electrical backup heater.
   - DHW availability can be assured without electrical backup heater if the right parameters combination is set during commissioning phase.
2. In terms of annual energy consumption:
   - The highest energy consumption is 24% higher than the one of the most efficient parameter settings (92 kWh/m² vs 74 kWh/m², for the same comfort level). This highlights the importance of commissioning parameters for heating energy efficiency.
   - The energy consumption is mainly dependent on the heating curve chosen. This parameter directly affects the energy consumption of the system. Indeed, the higher the heating curve, the lower the performance.
   - For the same comfort level (comfort levels lower than 24 hours/year), the 9 kW AWHP consumes more than the one of 12 kW. This is explained by the use of electric backup heaters (degradation of the SPF).
   - Water pump annual consumption is not negligible. It represents up to 15% of annual electricity consumption. This is

especially true when no indoor thermostat control is used for indoor air temperature regulation (as the system has no information to stop water pump when no heating needs are detected).

3. In terms of energy bill:
    - Annual electricity costs for space heating and DHW can vary from 970 € to 1208 € depending on commissioning parameters (tariff subscription costs are not included). This highlights again the importance of setting properly the adapted AWHP parameters to the dwelling.

To sum up we can say that the commissioning phase in residential AWHP directly affects comfort and energy efficiency performances. Air to Water Heat Pumps are high-energy efficiency technologies that are able to reduce CO_2 emissions for space heating and DHW generation. However, commissioning may affect its performances if the set parameters are not adapted to the dwelling.

This paper highlights the need of developing auto commissioning of double service Air to Water Heat Pumps in order to exploit their high-energy efficiency potential.

NOMENCLATURE

Abbreviations

AWHP = Air to Water Heat Pump
DHW = Domestic Hot Water
HP = Heat Pump
SH = Space Heating
SPF = Seasonal Performance Factor
TH = Thermostat
TRV = Thermostatic Radiator Valves

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