Dynamic Modelling and Control System Optimization of a Reversible Air-to-Water Heat Pump with Heat Recovery for Domestic Hot Water Production

Matteo Dongellini – University of Bologna, Italy – matteo.dongellini@unibo.it
Luigi Belmonte – University of Bologna, Italy – luigi.belmonte@studio.unibo.it
Gian Luca Morini – University of Bologna, Italy – gianluca.morini3@unibo.it

Abstract

Even if the energy demand for space heating/cooling of near zero energy buildings (nZEBs) is continuously decreasing due to the improvement of the insulation level of building envelope components, the energy requirement for domestic hot water (DHW) production cannot be similarly reduced: for this reason, the weight of DHW energy consumptions on the overall building energy performance is becoming more and more significant for nZEBs. A reversible heat pump with recovery of the condensation heat (HPHR) is one way to obtain significant energy savings and respond to this increasing influence of DHW production with respect to the energy demand in residential buildings, since this kind of device is able to simultaneously satisfy the energy needs for DHW production and space cooling during the summer season. In order to improve the energy efficiency of a HPHR, the heat recovery operating mode should be maximized during the cooling season: for this reason, a detailed analysis of the heat pump control system is needed. Heat pump performance strongly depends on the values of control parameters, which are influenced by the system working conditions, such as DHW draw-off profile, building heating/cooling load and thermal storage size. In this paper, a detailed analysis of the annual energy performance of a HPHR system is obtained by means of TRNSYS 17: several simulations are carried out by varying the control algorithm, in order to achieve the best seasonal performance factor of the system. The results reported present a series of rules for the best setting of the heat pump control system parameters to HVAC designers and heat pump manufacturers and highlight how significant energy savings can be achieved with the adoption of a HPHR with respect to traditional systems based on a gas boiler or a conventional heat pump without heat recovery.

1. Introduction

In recent years, the efforts of public and private bodies have aimed to reduce the energy demand of buildings: recent studies have demonstrated that, worldwide, residential and commercial structures are responsible for about 40% of the gross energy production (Krzaczek et al., 2019). Furthermore, in the European Union (EU) the residential sector alone is responsible for about the 25% of the total energy demand (Karytsas et al., 2019). For these reasons and due to increasingly negative environmental impacts, new constructions in the EU are required to comply with the near Zero Energy Building (nZEB) requirements by 2020 (EU, 2010). If the residential sector is considered, space heating (SH) accounts for the majority of the overall energy demand, followed by space cooling (SC), cooking, lighting and Domestic Hot Water (DHW) production (Krzaczek et al., 2019); when only the heating energy consumption is taken into account, DHW preparation represented approximately 19% of the total energy need of European residential buildings in 2013 (Kitzberger et al., 2019). Furthermore, the relevance of DHW production is continuously increasing in nZEBs: as improvements in building thermal insulation are made, so space heating/cooling energy demand is reduced, but hot water demand cannot be similarly decreased. For this reason, the contribution of DHW energy consumption may reach 50% of the total energy need of this kind of buildings (Bertrand et al., 2017).

Heat pumps are considered a suitable solution to decrease the primary energy consumption of buildings: these devices represent an effective alternative to traditional systems, such as boilers and

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electric resistances, for DHW production and SH. Furthermore, reversible units are able to provide all the energy services in a building with a single device. In addition, in the residential sector air-source heat pumps (ASHPs) are the most wide-spread solution, due to the huge availability of heat sources, considerable efficiency and low installation costs (Wu et al., 2018).

Different solutions are currently proposed by heat pump manufacturers for DHW preparation. In order to prepare high temperature DHW in centralized systems, state-of-the-art heat pump systems are typically equipped with a desuperheater, which is an additional heat exchanger installed between the compressor and the condenser of the unit (Hengel et al., 2016). Generally, with this kind of device the simultaneous production of hot water for SH at intermediate temperatures and for DHW at high temperatures is possible. A promising technology for DHW production is represented by CO2 heat pumps (Trinchieri et al., 2016): CO2 is a non-flammable, non-toxic fluid characterized by a null GWP, whose thermo-physical properties allow the achievement of high energy efficiency.

In addition, during a significant part of the summer season heating and cooling energy are simultaneously needed for DHW production and SC, respectively. Unfortunately, traditional reversible ASHPs reject condensation heat to the external heat sink (i.e. the outdoor air) during the cooling operating mode; this waste thermal energy could be recovered and used to prepare DHW when this dual energy demand is requested at the same time. In this paper, the dynamic model of a multi-function heat pump with recovery of the condensation heat (HPHR), able to simultaneously satisfy DHW production and cooling needs during summer, is presented. Several Authors (Byrne et al., 2009; Ghoubali et al., 2014; Naldi et al., 2015) have focussed their research on this kind of units and results have shown that significant energy savings can be achieved with respect to traditional heat pumps. In this work, the model of a reversible air-to-water HPHR, characterized by three heat exchangers (i.e. a fin-and-tube coil and two plate heat exchangers for refrigerant/air and refrigerant/water thermal exchange, respectively), is described. The model of the unit has been developed by means of the software TRNSYS 17, and with the cooperation of a heat pump manufacturer, which provided the performance data for the possible operating modes of the unit. Several simulations were carried out by varying the control algorithm of the HPHR in order to evaluate the optimal control management of the heat pump and to achieve the best seasonal energy performance.

2. Methodology

2.1 Simulation Layout

The dynamic model of the HPHR was coupled to a reference residential building. Both the heat pump system and the building was set up within TRNSYS environment, with a holistic approach. The reference construction considered in this paper is a well-insulated, detached building described in Dongellini et al. (2019); a 3D view of the house is shown in Fig. 1.

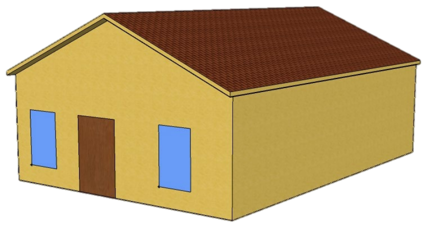

Fig. 1 – 3D view of the reference building

It is important to highlight that in this work the building heating/cooling load was modified with respect to that obtained in the work of Dongellini et al. (2019). The detached house was located in Palermo (lat. 38°6' North, long. 13°20' East, South of Italy); the thermal insulation of the building envelope had also increased: for example, the U-value of external walls had decreased to 0.34 W/m²K. In accordance with current Italian law, the heating period was fixed to four months (December 1st – March 31st), while the cooling period to six months (May 1st – October 31st). Furthermore, the energy demand for DHW production was evaluated in accordance with Italian Standard UNI/TS 11300-2 (UNI, 2014): according to the methodology reported by this Standard for the residential sector, the daily hot water need of the reference building is equal to almost 120 litres. Furthermore, the hourly profile introduced by Standard UNI/TS 11300-4 (UNI, 2012) was used to define the hot water draw-off request: this is characterized by a smooth profile, with a maximum DHW draw-off equal to 16 l/h.

The whole dynamic model set up in this work is reported in Fig. 2. The behaviour of the heating system components was simulated by means of standard and TESS libraries elements. The storage tank for DHW production is a stratified vertical cylinder, divided into 5 vertical nodes with the same volume, characterized by a couple of inlet/outlet ports and an immersed coiled heat exchanger (Type 534 with HX). The tank is filled with technical water, heated by the heat pump, while the freshwater flows within the internal heat exchanger. Furthermore, the loss coefficient of the storage was set to 0.38 W/m²K.

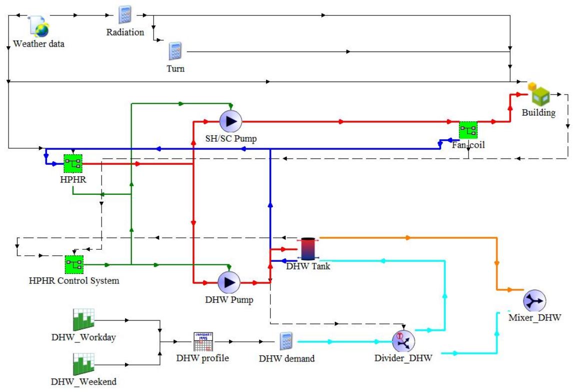

Fig. 2 – Layout of the developed TRNSYS model

Heating/cooling energy is delivered to the building by means of two-pipe three-speed fan-coils; four units were installed in the flat, one for each room, and they were sized on the basis of the zone cooling peak load. As will be seen later, the building cooling load is significantly larger than the heating required load. Fan-coil performance data at full and at partial load were provided by the manufacturer and were included within the External File schedule of Type 996.

2.2 HPHR Modelling

As reported in the Introduction of this paper, a HPHR is a device able to provide heating and cooling energy at the same time. In Fig. 3 the logical scheme of an air-to-water HPHR is shown.

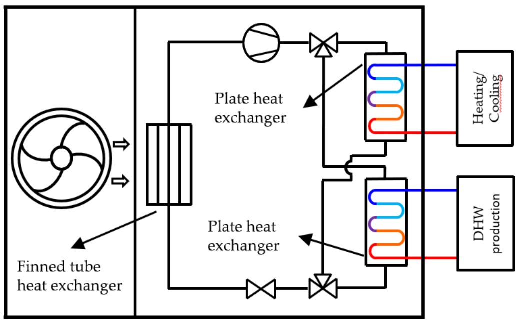

Fig. 3 – Logical scheme of an air-to-water HPHR

More specifically, a HPHR has three possible operating modes: heating mode (for SH or DHW production only), cooling mode (for SC only) and heat recovery mode (DHW production and SC at the same time). It is evident that this kind of device is equipped with three heat exchangers and a pair of three-way valves: depending on the unit operating mode the refrigerant fluid circuit varies and the heat pump performance changes. The heat exchange between the refrigerant and the external air occurs within the finned-tube coil, which operates as evaporator and condenser during heating and cooling working mode, respectively, while it is bypassed in heat recovery mode. On the other hand, the load side plate heat exchanger has the function producing hot (cold) water for space heating (cooling): for this reason, it is the condenser of the unit when only SH is needed and the evaporator during cooling and on heat recovery mode. Finally, the plate heat exchanger dedicated to DHW production is active only when hot water for sanitary use is needed (with or without a simultaneous request of SC): this element always operates as a condenser.

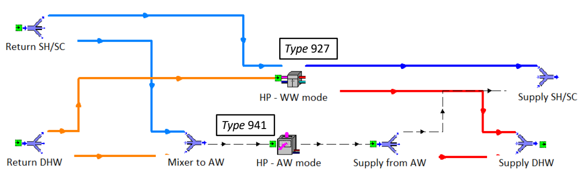

Fig. 4 – Dynamic model of the HPHR set up in TRNSYS

A Type which simulates the behaviour of a HPHR is not included within TRNSYS libraries. Consequently, a innovative subroutine was developed, in order to evaluate the performance of this kind of device. Generally, the HPHR considered in this work has two different operating modes: when heat recovery mode is possible, both the plate heat exchangers are active and the heat pump operates as a water-to-water unit; by comparison, during working modes in which only SH, SC and DHW production are needed the heat pump operates as a traditional air-to-water device. For this reason, the performance of the HPHR is calculated by means of standard Types 927 and 941 for water-to-water and air-to-water operating modes, respectively. In Fig. 4, the TRNSYS model of the HPHR developed in this work is shown: the heat pump control system, described in the following Section, selects the active Type based on the building loads.

2.3 Management of the System

The HPHR operating mode is defined by the management system according to different signals, depending on the season and the building loads.

In accordance with the standard heating/cooling periods reported in Section 2.1, SH mode is allowed only during the heating season, SC and heat recovery can be activated only during the cooling period while DHW production is potentially usable for the whole year.

On the other hand, the activation of the heat pump also depends on the effective load of the building. SH and SC working modes are, of course, activated when the conditioned zones need heating and cooling energy, respectively. In this case, the monitored variable used by the control system is the return water temperature $T_{w,in}$ (i.e. the temperature of the water entering the unit) and not the indoor air temperature directly, which is instead used by the fan-coil management system. The algorithm defined for SH is shown in Fig. 5(a); since the HPHR considered in this work is a single-stage device, the compressor has only two possible states: device switched on or switched off. For this reason, an on-off logic, characterized by a hysteresis cycle, is adopted: if the unit is switched off, it is activated when $T_{w,in}$ becomes lower than the threshold value $T_{ON;SH}$. The heat pump is then switched off when $T_{w,in}$ rises above the other threshold value $T_{OFF,SH}$.

The management approach for SC, represented in Fig. 5(b), is based on a similar algorithm: in this case, if the HPHR is active it is switched off when $T_{w,in}$ is lower than the threshold value $T_{OFF;SC}$ and then it is reactivated as soon as $T_{w,in}$ becomes higher than the parameter $T_{ON;SC}$.

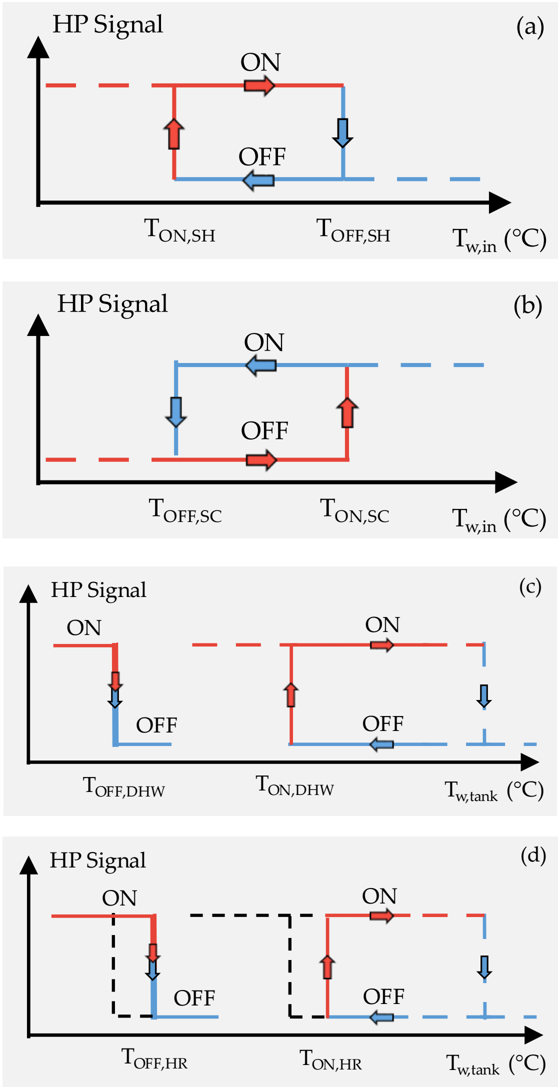

Fig. 5 – HPHR control algorithms for space heating (a), space cooling (b), DHW production (c), heat recovery (d)

In Fig. 5(c) the control logic for DHW production working mode is reported. The heat pump is controlled by monitoring the temperature of water within the storage tank at different heights ($T_{w,tank}$). More specifically, when the water temperature in the upper part of the tank falls below the threshold $T_{ON,DHW}$ following a hot water draw-off, the HPHR is activated in DHW production mode, even if thermal energy for SH is required. This operating mode is active until the tank has completely heated up: when the temperature in the lower part of the storage exceeds the threshold value $T_{OFF,DHW}$, DHW production mode is disabled. It is important to highlight that the values of both parameters should be set to ensure a DHW temperature flowing out of the tank of above 40°C.

As discussed in previous sections, heat recovery mode is activated only following a simultaneous request for SC and DHW production. For this reason, HPHR operates in this mode if both services are needed (i.e. if $T_{w,in}$ is higher than $T_{ON;SC}$ and the DHW tank temperature decreases following a hot water draw-off); as will be further discussed in the following section, in order to extend the duration of heat recovery mode different values of the threshold parameters for the activation/deactivation of the tank heating (i.e. $T_{ON,DHW}$ and $T_{OFF,DHW}$) should be defined if cooling energy is required (with heat recovery potentially possible) or not. As shown in Fig. 5(d), both the threshold values are increased and are identified as $T_{ON,HR}$ and $T_{OFF,HR}$ during heat recovery mode.

Different values in the threshold parameters for the management of DHW production and heat recovery modes were tested in order to investigate the potential decrease of the overall energy consumptions for SH, SC and DHW production along the year. In Section 3.1 the optimization of the HPHR control algorithm will be discussed and the optimal values of the unit control system will be shown.

2.4 HVAC system Characterization

The heat pump performance data for each possible operating mode (i.e. heating mode, cooling mode and heat recovery mode) were obtained from the unit technical datasheet and have been imported within TRNSYS through external files. It is important to stress that these data have been validated by the heat pump manufacturer by means of experimental measures conducted in a climatic chamber. In Fig. 6, a subset of the HPHR characteristic curves is reported: more specifically, in Fig. 6(a) and Fig. 6(b) the unit performance data (i.e. heating/cooling capacity and *COP*/*EER*) are shown for different values of external air temperature and with the inlet water temperature fixed to 40°C for SH mode (Fig. 6(a)) and to 12°C for SC mode (Fig. 6(b)). The heat pump performance data during heat recovery mode are reported in Fig. 6(c): *EER*, heating and cooling capacity are shown as a function of the return water temperature.

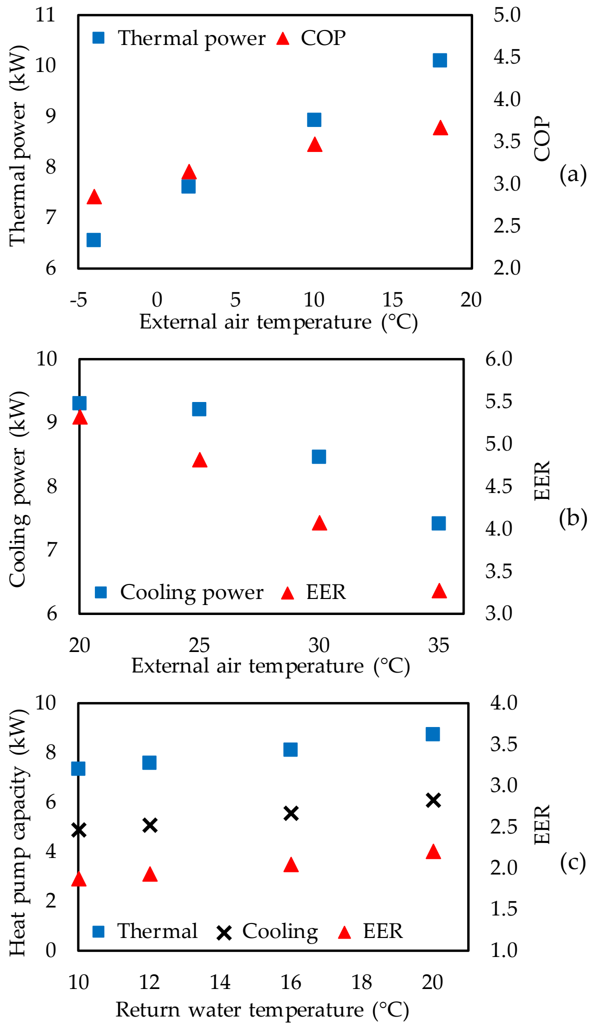

Fig. 6 – HPHR performance data for heating mode (a), cooling mode (b) and heat recovery mode (c)

3. Results and Discussion

The results of the simulations mainly relate to the seasonal energy performance of the HPHR during the cooling season and the percentage of DHW production energy need covered during heat recovery mode: these results are reported in Table 1 for different settings of the heat pump control system.

3.1 Optimization of HPHR Control Logic

In a first series of simulations, the optimal values of the parameters introduced in Section 2 for the management of DHW production were assessed. Different settings of the control algorithm were considered: in Table 1 the main results obtained with the tested combinations *($T_{OFF,DHW}$ - $T_{ON,DHW}$ / $T_{OFF,HR}$ - $T_{ON,HR}$)* are reported. More specifically, the threshold values for the activation and deactivation of DHW production mode $T_{ON,DHW}$ and $T_{OFF,DHW}$ were varied within the range [35°C-42°C] and [43°C-45°C], respectively; on the other hand, the threshold values for heat recovery mode (i.e. $T_{ON,HR}$ and $T_{OFF,HR}$) were ranged between 40°C and 47°C and 43°C and 50°C, respectively.

With reference to the obtained results, the best setting of control system parameters *($T_{OFF,DHW}$-$T_{ON,DHW}$ / $T_{OFF,HR}$-$T_{ON,HR}$)* is (42°C-45°C / 47°C-50°C): for this combination, the Seasonal Performance Factor (*SPF*) of the heat pump during the summer season, which takes into account both SC and DHW production, increases by approximately 9% when compared to the reference case, characterized by no differentiation between the control algorithms for DHW and HR modes. This is a consequence of a twofold effect: first, the heat pump performance for SC slightly decreases, with a reduction of *SPF* of about 3%, while the heat pump seasonal performance for DHW production is enhanced by approximately 48%. In HR mode, the heat pump cooling performance is reduced with respect to SC mode, due to higher condensation temperatures, but free thermal energy is obtained for DHW preparation.

Table 1 – Energy performance of the HPHR system during the summer season for different settings of the management system

Control system setting ($T_{OFF,DHW}$ - $T_{ON,DHW}$ / $T_{OFF,HR}$ - $T_{ON,HR}$)	Building service	Delivered energy (kWh)	Electric energy input (kWh)	Primary energy demand (kWh)	*SPF*	HR mode / DHW production (%)
40°C-43°C / 40°C-43°C	SC	3246	762	1905	4.25	0.18
	DHW	1525	388	969	3.93	
	Total	4771	1149	2874	4.15	
35°C-43°C / 40°C-43°C	SC	327	762	1906	4.25	0.05
	DHW	1517	368	918	4.13	
	Total	4764	1130	2824	4.23	
40°C-43°C / 42°C-45°C	SC	3246	762	1906	4.25	0.05
	DHW	1525	388	970	3.93	
	Total	4771	1150	2876	4.15	
40°C-43°C / 47°C-50°C	SC	3246	782	1955	4.15	24.85
	DHW	1530	295	739	5.18	
	Total	4775	1077	2694	4.43	
42°C-45°C / 47°C-50°C	SC	3247	793	1983	4.10	30.13
	DHW	1532	263	658	5.83	
	Total	4779	1056	2641	4.53	

Furthermore, it has been demonstrated that when SC is needed and, thus, HR mode is possible, the best energy performance can be achieved by increasing both threshold values $T_{ON,HR}$ and $T_{OFF,HR}$, in order to extend the duration of HR mode. With the reference configuration, the contribution of HR mode for DHW production energy need is negligible (lower than 1%, see Table 1); in comparison, by optimizing the system management almost 30% of the energy demand linked to hot water preparation is covered during HR working mode, with significant energy savings.

Finally, the annual energy performance of the HPHR for all building services (i.e. SH, SC and DHW production) was calculated and compared to that of traditional systems based on: i. a condensing gas boiler, for SH and DHW production, and an air-to-water chiller for SC; ii. a reversible air-to-water heat pump without condensation heat recovery. It is important to highlight that the seasonal generating efficiency of the boiler, η_s was fixed at 1.04, while chiller and heat pump were characterized by the same energy performance of the HPHR during heating, cooling and DHW production modes. Furthermore, the optimal setting of the HPHR control parameters, defined in the previous part of this paper, was considered.

In Table 2 the annual energy performance of the studied systems is shown: the seasonal efficiency η_s, the heating/cooling energy delivered to the building (E_{del}), the energy absorbed by the generating devices (E_{abs}) and the corresponding primary energy need (E_{pr}) are reported.

Results show that significant energy savings can be obtained with the adoption of a HPHR: the annual performance factor for this kind of system is 38% and 11% greater with respect to traditional systems based on two generators (i.e. a boiler and a chiller) or a heat pump without heat recovery, respectively. Moreover, more interesting results can be obtained if only the energy performance of the system for SC and DHW are taken onto account: by using a HPHR the primary energy need linked to these services is reduced by 26%, if compared to the first system, and by 10% if compared to a traditional reversible heat pump. Finally, the results obtained in this work highlight that the primary energy demand for DHW production can be dramatically reduced with the adoption of a HPHR characterized by optimized control management: in this case, the energy demand for DHW preparation is lowered by up to 70% and 46% with respect to the gas boiler and the conventional heat pump, respectively.

Table 2 – Annual energy performance for the simulated cases

Case	Service	E_{del} (kWh)	E_{abs} (kWh)	E_{pr} (kWh)	η_s
Boiler + chiller	SH	1677	1618	1637	1.04
	DHW	1741	1681	1693	1.04
	SC	4201	969	2397	1.79
	Total	7657	/	5727	1.36
HP without HR	SH	1676	487	1198	1.42
	DHW	1726	401	983	1.78
	SC	4201	969	2397	1.79
	Total	7641	1857	4577	1.69
HPHR	SH	1612	469	1154	1.42
	DHW	929	221	540	1.74
	SC	3650	823	2036	1.83
	HR (SC)	644	181	454	3.24
	HR (DHW)	825			
	Total	7660	1693	4185	1.87

4. Conclusion

In this work the dynamic model of a reversible air-to-water heat pump with condensation heat recovery (HPHR), able to simultaneously satisfy space cooling and DHW production needs, was developed by means of TRNSYS. Since this kind of heat pump is not included within the standard library of the software, an innovative dynamic model, able to calculate the energy performance of the unit in correspondence of all the possible working modes, was developed. The numerical results confirm that in order to increase the energy performance of the system, the period in which the heat pump operates in heat recovery mode (i.e. with the simultaneous production of DHW and cooling energy) must be expanded by optimizing the unit control management, which will vary according to the heat pump working mode (heating, cooling or heat recovery). The unit operating mode is defined by the temperature of the water stored in the stratified DHW tank, measured at different heights: more specifically, when the water temperature in the upper part of the storage drops below a threshold value, the heat pump must be activated to charge the DHW tank; furthermore, the unit is deactivated when the temperature in the lower part of the storage exceeds a second threshold value. In order to extend the duration of heat recovery mode, the optimal values of the above-mentioned threshold temperatures were assessed and results show that these values depend on the HPHR working mode: when space cooling is needed and heat recovery mode is possible, both values should be increased to achieve the best energy performance. Moreover, the results obtained highlight how the annual energy performance of a HPHR is much higher (by up to 38%) with respect to those of traditional systems based on a gas boiler or a conventional heat pump without heat recovery, due to significant energy savings linked to heat recovery mode during the summer season.

The results outlined in this paper suggest a series of rules for the optimal setting of the heat pump control algorithm to HVAC designers and heat pump manufacturers: it has been demonstrated that by optimizing the management of the heat pump it becomes possible to extend the duration of the heat recovery mode of these kinds of units, thus increasing the overall energy performance of the system.

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