July 2018

Design of a System for the Production of Domestic Hot Water from Wastewater Heat Recovery Based on a Heat Pump Optimized to Work at High Water Temperature Lift

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Hervas, Estefania; Marchante, Javier; Navarro-Peris, Emilio; and Corberan, Jose Miguel, "Design of a System for the Production of Domestic Hot Water from Wastewater Heat Recovery Based on a Heat Pump Optimized to Work at High Water Temperature Lift" (2018). *International High Performance Buildings Conference.* Paper 259.
https://docs.lib.purdue.edu/ihpbc/259

Design of a system for the production of domestic hot water from wastewater heat recovery based on a heat pump optimized to work at high water temperature lift.

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ABSTRACT

Sewage water or water from condensing loops are potential heat sources that usually are wasted although they usually have slightly higher temperature than the ambient (20-40ºC). Water-to-water heat pumps (WtWHP) for space heating, cooling or water heating applications are a mature technology that can use this heat in order to produce domestic hot water with high efficiency.

In previous works, some heat pumps prototypes has been developed in order to perform this operation with a high efficiency and some alternatives has been proposed in order to adapt the vapor compression cycle to this kind of application with a high hot water temperature lift.

The main objective of the present work is to study the best system configuration in order to use the wastewater heat to satisfy a hot water demand with a WtWHP. The solution is based on the HP prototype presented in (Miquel Pitarch, 2017) a preheater recovery heat exchanger (HE) and a hot water variable volume storage tank (DHW-st).

The HP is optimized from the exergetic point of view to work with high water temperature lifts in the condenser with subcritical conditions and high COPs. This is possible by the integration of a control system that optimizes the subcooling in the condenser based on external conditions. This configuration and operation allows the HP to operate with COPs up to 6 based on external conditions.

A model of the whole system using the Trnsys software has been developed and based on it, the size of the binomial HP- DHW-st has been analyzed for different DHW demand profiles. This work shows the importance of the proper sizing of these components in order to optimize the system performance. Finally, the HP CO2 emissions compared to gas boiler has been analyzed.

1. INTRODUCTION

To reach the objectives for the reduction of CO2 emissions, the use of more efficient technologies for heating is mandatory. In this line, the European Union is encouraging the use of heat pumps (HP) for heating and for DHW. Derived from that an increase of the heat pump market is expected in the near future. This will imply the use of them not only for heating and cooling in buildings but also in other applications like DHW where their market has been very limited up to now.

This will implies also that the design of the heat pumps must be adapted to each specific application in order to maximize the efficiency of the systems. For instance, in order to adapt the heat pump for DHW production using air as a heat source the use of transcritical cycles has been quite common (Nekså, 2002) or (Stene, 2007). In this line, in the last years subcritical cycles have been also adapted to work in these conditions (Pitarch, Navarro-Peris, Gonzálvez-Maciá, & Corberán, 2017) reaching also high levels of performance.

In order to optimize the efficiency of the system the recovery of waste heat from sewage water or condensation loops is an application of increasing interest nowadays (Frijns, Hofman, & Nederlof, 2013), (Meggers & Leibundgut, 2011) and in the review of different heat pump sources done in (Hepbasli, Biyik, Ekren, Gunerhan, & Araz, 2014).

At this moment, the development of heat pumps using waster heat as a heat source to produce DHW is a relatively new application and the optimization and characterization of these systems is still an open topic. In fact, regardless the small number of components involved in this application, a general view and knowledge of the system becomes very complex due to all the influent parameters.

Most of the common works done in this field lack of generality usually presenting a solution for a specific problem. For instance, in (Baek, Shin, & Yoon, 2005) a DHW production with a WWHP in combination to solar located in

Korea is presented, or in (Tammaro, Montagud, Corberán, Mauro, & Mastrullo, 2015) where authors analyze the best solution for a water to water heat pump in a hotel located in an specific place but out of the boundary conditions, the results may not be applicable.

Understanding the system and the relationship among the components in order to extract not only problem-specific solutions but also general conclusions would be helpful for a wider public.

In this work, a model of a DHW production system using Trnsys (University of Wisconsin--Madison. Solar Energy Laboratory, 1975) software has been developed. The model is based on a high performance water to water HP working with propane previously optimized and validated in (Miquel Pitarch i Mocholí, 2017). The presented work aims to introduce this WtWHP into a DHW system composed by it a preheater recovery heat exchanger (HE) and a variable volume DHW storage tank to analyze and optimize the performance of the system that will be the real application of the WtWHP. Based on the model, several studies have been carried out in order to find the optimal WtWHP-DHW storage tank size for different demand profile shapes and consumptions. This will allow to gain insight in the whole system response depending on the demand and which should be the basic criteria in order to size it in the most proper way. Finally, the CO2 emissions incurred by the DHW production with the heat pump are obtained and compared to the emissions generated by a gas boiler (common used technology for DHW production).

2. SYSTEM DESCRIPTION

The system has been configured in order to produce DHW for the residential sector. Nevertheless, any application where a hot water demand is required and a wastewater flow at temperature slightly higher than the ambient is available could be used.

Figure 1 shows the layout of the system. The main components included in the system are: a heat exchanger (HE) that allows the increase of the system's efficiency according to the study done in (Hervas-Blasco, Pitarch, Navarro-Peris, & Corberán, 2017), a heat pump (HP) and a DHW storage tank with variable volume.

There are two different water circuits:

- Grey water circuit: it is represented in grey and belongs to the wastewater mass flow rate. First, the wastewater flows are collected and derived to a storage tank (septic tank) from which the required mass flow is extracted. The heat contained in this flow is first recovered through a HE and then, it pass to the HP as a heat source from where it leaves to the sewage.
- Fresh/tap water circuit before the HP: it is represented in dark blue and includes the tap water from the net. This flow is preheated by recovering part of the grey water heat in the HE. Thereafter, the HP heats the water up to required levels and flows into a variable volume (uniform temperature) tank, represented in brown. The hot water extracted from the tank is represented in red and the water at demand temperature is represented in orange.

The temperature values shown in Figure 1 are only average temperatures for a residential application used only as an example.

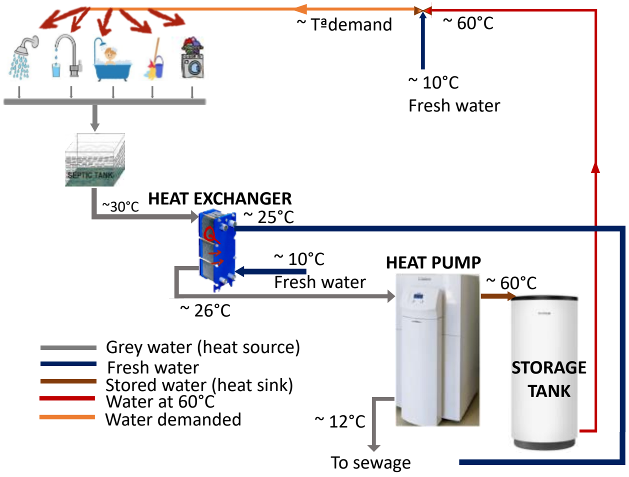

Figure 1: WWHP system layout

The thermal efficiency of this type of systems depends mainly on external conditions and design/sizing of the components. The legislation policies demand characteristics (profile shape, required satisfaction, quantity and temperature), grey water characteristics (profile shape, quantity and temperature), water supply (net) temperature and ambient temperature are the most important external factors. They depend mainly on the user and its location.

The sizing of the components is conditioned to the external conditions, the performance of the components and the interrelation among all the elements of the system. In fact, the optimal operation of one component may not result on the best solution of the system. An example of it occurs with the addition of the HE to preheat the water before it enters the condenser. Warmer water at the entrance of the condenser penalizes COPhp but enhances the performance of the system COPsys.

Furthermore, the most convenient solution to the user may rely on economic factors (investment costs and operating expenses such as electricity price, CO2 policies, alternative fuel's price and/or availability). However, their values depend on specific organisms and the values may change through the life-time of the system keeping away from general studies.

In order to fix the problem, only energetic implications are considered in this work.

3. PERFORMED SIMULATIONS

3.1 Model Description

Figure 2 shows the model in Trnsys. Trnsys types available in the open literature has been used for all the components except the heat pump. Type 39 has been used for the variable volume tank, Type 5b is used for the HE and the types 742 and 709 are used for the auxiliary water pumps and pipes. The used HP was a prototype with very specific characteristics and a dedicated type was done in order to integrate it in the whole system. The model is described in the following subsection and is based on a previous experimental characterization of it

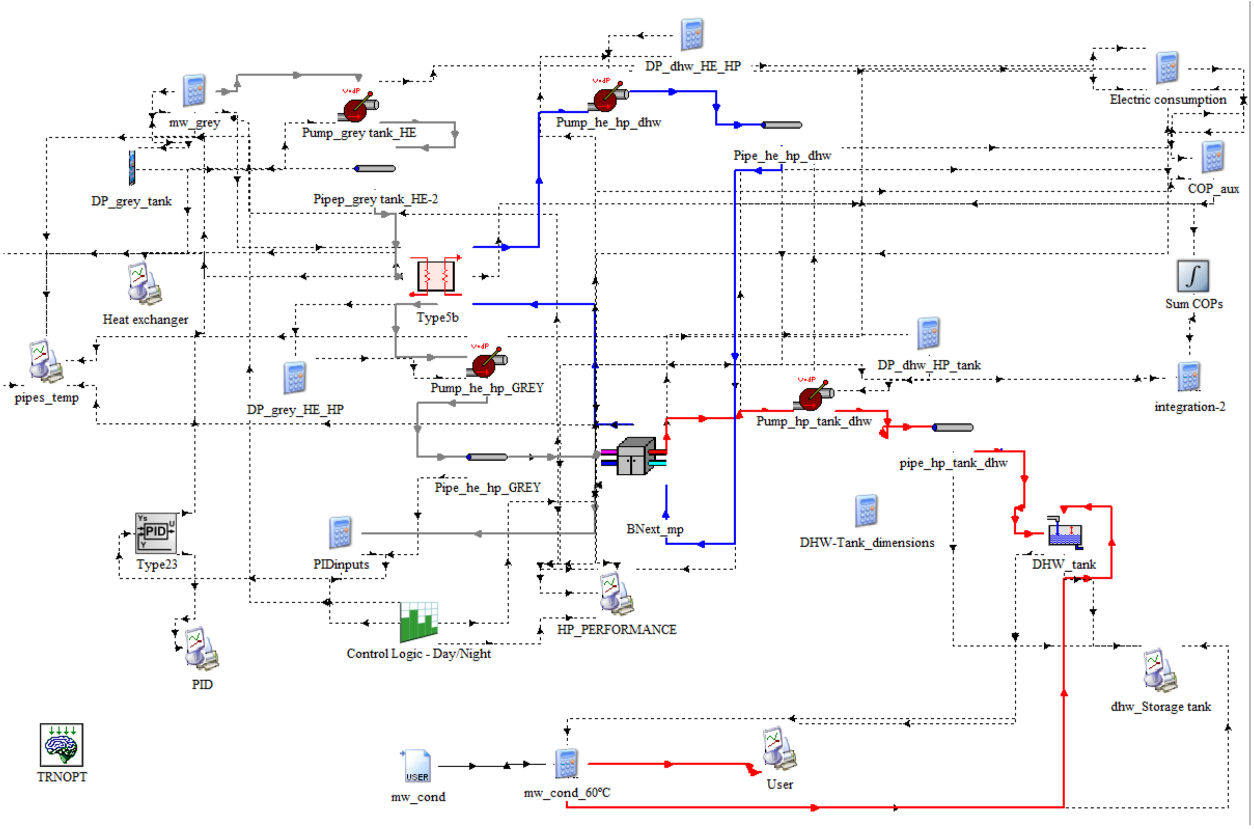

Figure 2: WWHP system Trnsys layout

3.2 Heat pump type

This type has been developed to describe the behavior of a water-to-water heat pump working with propane and able to operate with high COPs thanks to the optimization and control of the temperature match between the primary and secondary fluids in the condenser and in the evaporator.

The most relevant characteristics of this HP is that the expansion valve is able to control of the subcooling instead of the superheat placing a liquid receiver at the inlet of the compressor. For further details of the heat pump characteristics, please refer to (Miquel Pitarch i Mocholí, 2017) and for the implemented control algorithm to (Hervas-Blasco, Pitarch, Navarro-Peris, & Corberán, 2018).

The prototype has been experimentally tested with a test campaign consisting in more than 50 test. It was modeled using IMST-ART software (José Miguel Corberán, 2009) and the model was validated using the performed test.

In order to build the corresponding type in trnsys, the heat pump model was used to generate 3569 operating points, and correlations for the energy consumption, heating and cooling capacity of the heat pump as a function of the external operation parameters was developed. The considered external parameters were water inlet and outlet temperatures in the evaporator and in the condenser.

Table 1 collects the range of temperatures of the secondary fluid (sink and source) included in the study. Notice that only the feasible cases have been considered (for instance, the outlet water temperature at the evaporator is always lower than the inlet water temperature at the evaporator). Furthermore, superheat is fixed to zero and the optimal subcooling is calculated as a liner function of the water temperature lift at the condenser according to (Hervas-Blasco, Pitarch, Navarro-Peris, & Corberán, 2018).

Table 1: External conditions simulated in IMST-ART to obtain the type of the HP for Trnsys

	Temperature Range [ºC]
Evaporator water inlet temperature	5-45
Evaporator water outlet temperature	2-42
Condenser water inlet temperature	5-60
Condenser water outlet temperature	40-90

The inputs of the type are the DHW production and temperature and the water inlet temperature at the inlet of the evaporator and condenser.

The correlation obtained for the cooling capacity was:

$$Q_{evap\_corr} = f(Q_{cond}, T_{ei}, T_{ci}, T_{co}) = c_0 + c_1 T_{ei} + c_2 m_{we} + c_3 T_{ci} + c_4 Q_{cond} + c_5 Sc_{opt} \tag{1}$$

Where Sc_{opt} is calculated from a linear expression function of the secondary temperature lift at the condenser (experimentally validated in (Hervas-Blasco et al., 2018) and c0=45.1084, c1=0.00361, c2=0.0325, c3=-0.01672, c4=0.9527, c5=-0.1598.

The outlet evaporator temperature is directly obtained from the general heat transfer equation as it is shown in Eq. 2

$$T_{eo} = T_{ei} - \frac{Q_{evap}}{m_{wevap} cp} \tag{2}$$

The correlation obtained for the compressor work as a function of the water outlet temperatures and the condenser inlet temperature was

$$\begin{aligned} W_{c\_corr} &= f(T_{eo}, T_{ci}, T_{co}) = \\ & c_0 + c_1 \cdot (T_{co} - T_{ci}) + c_2 T_{eo} + c_3 T_{co} + c_4 T_{eo}^2 + c_5 T_{co}^2 + c_6 T_{co}^3 + c_7 T_{co} T_{eo}^2 + c_8 T_{eo} T_{co}^2 \end{aligned} \tag{3}$$

Where c0=-2.345e+02, c1=-1.320e-02, c2=3.669e+00, c3=-1.035, c4=-1.284e-02, c5=2.801e-03, c6=6.055e-06, c7=3.717e-05 and c8=-3.018e-05.

The heat pump performance (COP_{hp}) calculation is done directly from the above correlations according to Eq. 4

$$COP_{hp} = Q_{cond\_corr} / W_{c\_corr} \tag{4}$$

The maximum error occurs for the compressor work and is 10% but only within a few points. Cooling capacity has 3% of error.

Finally, the performance of the system (COP_{system}) is obtained from the model by considering the total heating capacity and the total electric consumption as it is indicated in Eq. 5.

$$COP_{system} = (Q_{cond\_corr} + Q_{HE})/(W_{c\_corr} + \sum W_{pumps}) \qquad (5)$$

Where W_{pumps} is the electric consumption of the auxiliary water pumps.

3.3 Model contour conditions

The rest of the system conditions has been defined as:

a)Water conditions: Wastewater (grey water) has been assumed at 30ºC and no limit about its availability has been considered. Fresh/net water temperature of 10ºC. DHW demand of 60ºC due to legionella requirements.

b) Heat exchanger size: defined in order to have a DT of 5K between the grey inlet temperature and the fresh water outlet temperature.

c)Storage tank: The volume of DHW water stored in the tank is variable (no stratification assumed) and the insulation of it is based on the requirements specified in the Spanish legislation RITE 07, IT 1.2.4.2.1.2. The initial volume (Vini) and the volume (Vtank) characterize the tank. In all cases the geometry of the storage tank has been considered as a cylinder with H/D=4.

d) Heat pump size: The type was developed for an specific heat pump size but in real applications the HP size is a variable that must be calculated. Therefore the type model include an scale factor in such a way that the heat pump size could be defined in order to satisfy the required demand. The used criteria in order to define the heat pump size has been based on the fact that at the end of the day it must equal the daily demand. Thus, the production would be the average consumption through the operating HP time. This criterium put a limit in the minimum allowed hp size but also in the maximum storage tank volume.

Under these assumptions, the optimal size (minimum size) of the components has been calculated in order to have empty the tank at some point of the day, to supply the required demand at the required time and to keep the same level at the start and the end of the day (heat pump production equals to demand).

3.4 Analyzed cases

The study is composed in the 8 cases shown in Table 2: cases 0-3 the average SHW demand is kept constant and the influence of the profile shape on the tank volume is analyzed assuming a constant production during the 24h of the day. In cases 4-6, the variation of the operating period has been considered. This situation may be interesting for instance, when there is a variation of the electricity price with time. In these cases, for the average profile day of Figure 4a, three operating times have been considered to analyze the influence of the heat pump size and operating time on the storage tank volume assuming a constant production. Finally, two different profiles with the same shape as the one in Figure 4a but different average consumption are also considered to understand the size of the heat pump and the tank volume relation (for constant production) related to the demand quantity.

Table 2: Description of the studied cases

Case	Description	
0	*Constant demand*	
1	*One peak profile with different sizes and positions*	
	a	Peak = 0.3 times the average SHW demand at 8h
	b	Peak = 5 times the average SHW demand at 8h
	c	Peak = 24 times the average SHW demand (max.) at 8h
	d	Peak=5 times the average SHW at 0h
	e	Peak=5 times the average SHW at 5h
	f	Peak=5 times the average SHW at 15h
	g	Peak=5 times the average SHW at 23h
2	*Two peaks profile with different sizes and positions*	
	a	Peaks = 0.3 times the average SHW demand at 8-9h
	b	Peaks = 5 times the average SHW demand at 8-9h
	c	Peaks = 12 times the average SHW demand (max.) at 8-9h
	d	Peaks=5 times the average SHW at 0-1h
	e	Peaks=5 times the average SHW at 0h -3h
	f	Peaks=5 times the average SHW at 0h - 19h
	g	Peaks=5 times the average SHW at 4h - 19h

	h	Peaks=5 times the average SHW at 15h - 21h
3	*Daily profile from an annual profile generated with DHWcalc tool with different shapes*	
	a	Average profile
	b	Profile of the day with the highest peak
	c	Profile with the latest peak
	d	Profile with the earliest peak
	e	Profile with middle-day peak
4	*Three periods distinction on the electric tariff with only production in during the off-peak time (0-8h)*	
5	*Two periods distinction on the electric tariff with only production in during the off-peak time (22-12h)*	
6	*Electricity from renewables (i.e. solar photovoltaic), only production during the day-light time (8-18h)*	
7	*One sleeping room house (1.5 people). Average consumption at 65ºC of 38.77l/day*	
8	*Multifamily house composed by 3 houses of 3 people. Average consumption at 65ºC of 232.61l/day*	

The daily DHW consumption is calculated in all the cases according to the 4.1 section of the Spanish DB-HE4. For cases 0-6, a house of 4 people, resulting in an average consumption of 112l/day of water at 45ºC (28 l/dayperson). That is, 103.4l/day at 60ºC for all the cases. Case 7 is 38.77l/day and Case 8 232.6l/day. For cases 3-8, an annual profile has been generated with the DHWcalc software (Jordan & Vajen, n.d.). The average consumption at 45ºC is set to 150l/day (cases 3-6), the number of people to 4 and houses to 1, the vacation period 14 days, the draw-off flow rates and the probability distribution function as well as the weekend adjustment are the default values and the step time is 1h while the duration is one year (8760h).

From the annual hourly profile generated, five daily shape variations are used in the Case 3: (a) an average profile, (b) the profile of the day with the highest peak, (c) the profile with the latest peak, (d) the profile with the earliest peak and a profile with a middle-day peak. Figure 3 represents the SHW daily demand for a 4 people house at 65ºC in each of the considered days.

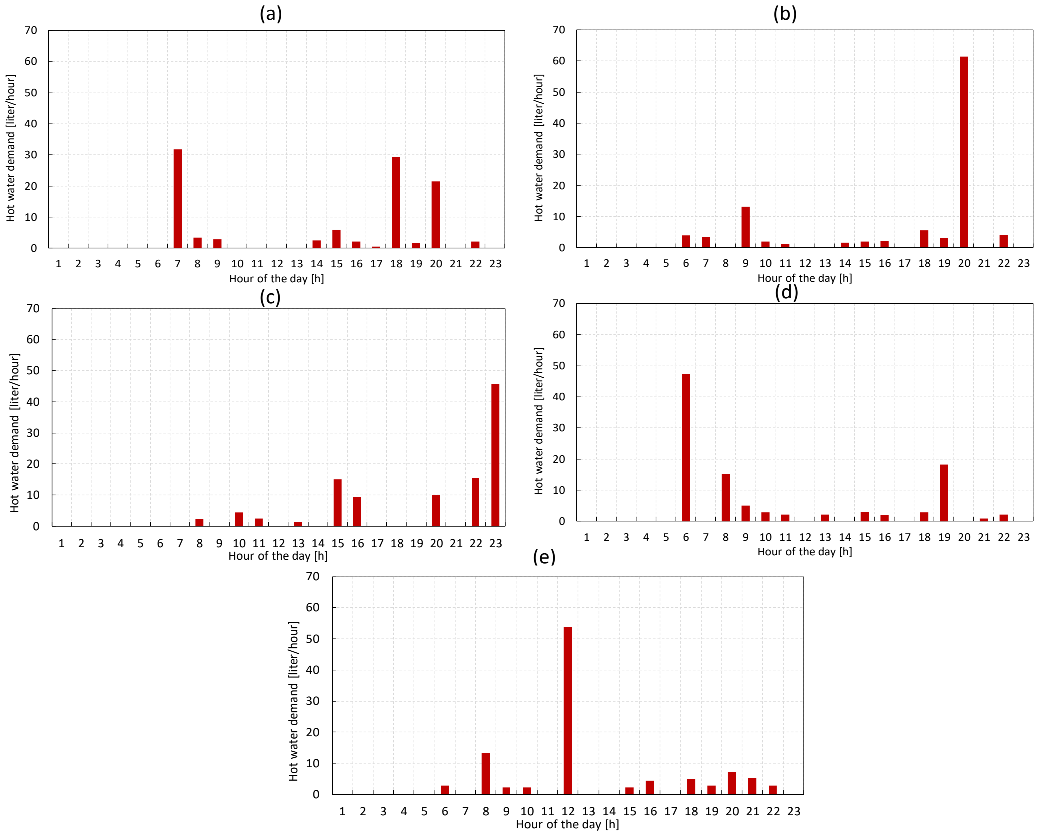

Figure 3: SHW daily demand for a 4 people house at 65ºC in (a) an average profile day, (b) the profile of the day with the highest peak, (c) the profile with the latest peak, (d) the profile with the earliest peak and a profile with a middle-day peak.

From the same shape of the profile reflected in Figure 4a, two profiles have been included in the study with different mean SHW demand: case 7 (1.5 people house) and case 8 (3 houses of 3 people). Figure 2 shows the considered profiles.

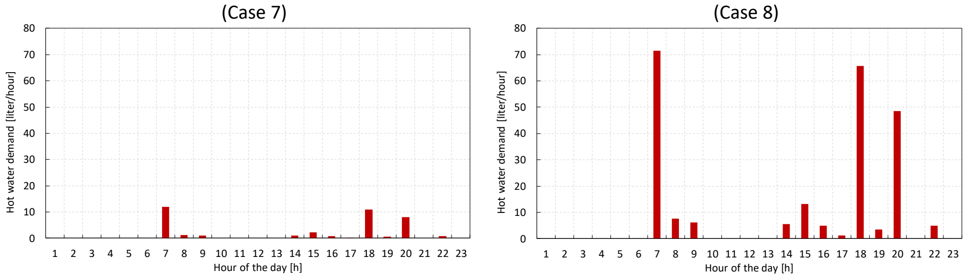

Figure 4: SHW daily demand for Case 7 (38.77 l/day) and Case 8 (232.61 l/day)

Finally, the total CO2 emissions derived from the DHW with the heat pump are calculated and compared with the same production by a gas boiler considering the conversion factors of Spain (MINETUR, 2018):

- 0.92 gas boiler efficiency factor (Spanish regulation default gas boiler efficiency)
- 1.19 factor conversion from natural source to primary energy from non-renewables.
- 1.954 factor conversion from conventional electric energy to primary energy from non-renewables.
- 0.331kg_{CO2}/kWh from conventional electricity energy source
- 0.252kg_{CO2}/kWh from natural gas energy source.

4. RESULTS

Table 3 shows the optimal volume of the tank (Vtank), the required initial volume (Vini), the heat pump size (in terms of the compressor power, Wc), the heating capacity of the HE (Qhe), the heating capacity of the HP (Qcond) and the minimum DHW tank temperature according to the specified conditions for all the cases.

Table 3: Heat pump and storage tank optimal sizes including the initial volume of the tank

Case	mwdemand [l/day]	mwhp [l/h]	Wc [W]	Vtank [liter]	Vini [liter]	Qhe [W]	Qcond [W]	Tmin_tak [ºC]	COPhp [-]	COPsystem [-]
0	103.4	4.31	34.01	0	0	75.07	175.15	-	5.15	7.36
1a	103.4	4.31	34.01	3	0.92	75.07	175.15	59.99	5.15	7.36
1b	103.4	4.31	34.01	17.23	12	75.07	175.15	59.99	5.15	7.36
1c	103.4	4.31	34.01	99	69	75.07	175.15	59.56	5.15	7.36
1d	103.4	4.31	34.01	17.23	17.23	75.07	175.15	59.99	5.15	7.36
1e	103.4	4.31	34.01	17.23	14.23	75.07	175.15	59.99	5.15	7.36
1f	103.4	4.31	34.01	17.23	6.75	75.07	175.15	59.99	5.15	7.36
1g	103.4	4.31	34.01	17.23	0	75.07	175.15	59.99	5.15	7.36
2a	103.4	4.31	34.01	6	1.92	75.07	175.15	59.99	5.15	7.36
2b	103.4	4.31	34.01	34.46	23.49	75.07	175.15	59.89	5.15	7.36
2c	103.4	4.31	34.01	94.77	64.6	75.07	175.15	59.57	5.15	7.36
2d	103.4	4.31	34.01	34.46	34.46	75.07	175.15	59.89	5.15	7.36
2e	103.4	4.31	34.01	31.33	31.33	75.07	175.15	59.89	5.15	7.36
2f	103.4	4.31	34.01	28.2	17.2	75.07	175.15	59.94	5.15	7.36
2g	103.4	4.31	34.01	21.93	10.97	75.07	175.15	59.91	5.15	7.36
2h	103.4	4.31	34.01	26.63	3.13	75.07	175.15	59.95	5.15	7.36

3a	103.4	4.31	34.01	40.93	10.77	75.07	175.15	59.87	5.15	7.36
3b	103.4	4.31	34.01	57.1	8.78	75.07	175.15	59.85	5.15	7.36
3c	103.4	4.31	34.01	56.63	6.47	75.07	175.15	59.85	5.15	7.36
3d	103.4	4.31	34.01	50.16	28.62	75.07	175.15	59.86	5.15	7.36
3e	103.4	4.31	34.01	49.85	22.5	75.07	175.15	59.86	5.15	7.36
4	103.4	12.93	102.03	90.47	0	225.20	525.46	59.57	5.15	7.36
5	103.4	7.39	58.31	64.32	12.63	128.71	300.32	59.84	5.15	7.36
6	103.4	10.34	81.59	86.27	31.8	180.09	420.21	59.59	5.15	7.36
7	38.77	1.61	12.70	15.35	4	28.04	65.43	59.99	5.15	7.36
8	232.61	9.69	76.46	92.1	24.23	168.77	393.79	59.84	5.15	7.36

All the storage tank volumes respond to the minimum value that satisfies the demand instantaneously. All the heat pump sizes are based on a constant production during the respective operating period in order to heat the water mass flow rate required by the demand at the end of the day (this condition can be seen by the restriction of having the same level of water in the storage tank at the start and end of the day). As an example, Figure 5 shows the results for the case 2h of the employed methodology.

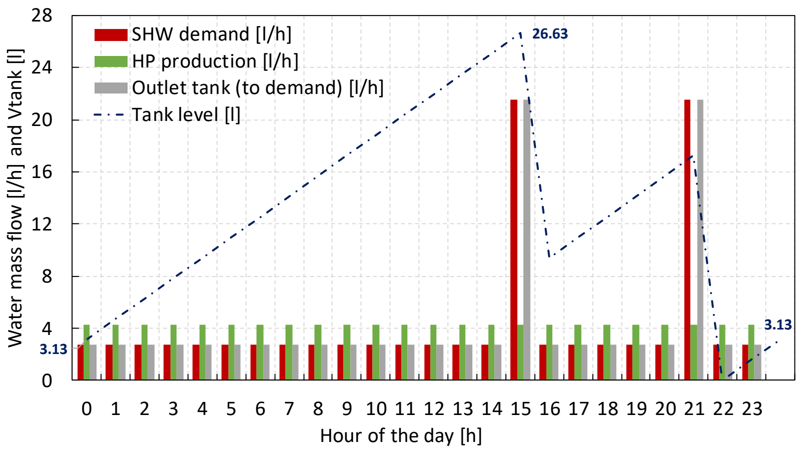

Figure 5: Level of the tank, SHW demand, production and outlet of the tank water mass flow rate during a day for the 2h case.

According to Table 3, the storage tank would not be required if the production could instantaneously supply the demand. This leads to an oversized heat pump (given by the maximum peak) that could be obtained with an inverter compressor.

If a smaller heat pump than the peak demand is desired or a fixed speed compressor is used, a storage tank would be needed. The most influent variables on the HP size are, the total DHW demand, the operating time and the storage volume. In fact, the operating time and the volume are directly related to the HP size. In addition, the DHW storage tank allows the HP to independence from the DHW demand profile. Thereby, with a proper tank sizing, the peak-off/peak periods do not influence on the HP size not being possible if the volume of the tank is not the proper one.

The most influent variables on the DHW storage tank volume are the shape of the demand profile and the HP production profile. The minimum required volume and initial volume that guarantees the demand supply is mostly influenced by the difference between the production profile and the demand profile with the time. The use of a water tank eliminates de necessity of using an inverter compressor and increase the efficiency of the system.

The proper definition of the user levels of comfort could decrease the ST volume significantly. Further analysis of this relationship needs to be done.

Finally, as it can be seen on Table 3, the losses in the storage tank to the ambient are lower than 0.5ºC for all the cases demonstrating that a variable volume tank may be a reliable solution for these type of applications.

The total energy demand, total electric energy consumed by the heat pump and the comparison with the production from a gas boiler in terms of daily CO2 emissions is shown in Table 4.

Table 4: Energy demand and production with a HP and a gas boiler. CO2 emissions results.

Case	mwdemand [l/day]	Energy demand [kWh/day]	Electric energy consumed HP [kWh/day]	Energy consumed gas boiler [kWh/day]	Final energy HP not renewable [kWh/day]	Final energy gas boiler not renewable [kWh/day]	CO2 emissions HP [kgCO2/day]	CO2 emissions gas boiler [kgCO2/day]
0-6	103.40	6.00	0.82	6.52	1.59	7.76	0.53	1.96
7	38.77	2.25	0.30	2.45	0.60	2.91	0.20	0.73
8	232.61	13.50	1.84	14.68	3.59	17.47	1.19	4.40

According to Table 4, the production of DHW water with a heat pump could lead to a reduction around 27% in the CO2 emissions compared to the same production with a gas boiler.

5. CONCLUSIONS

In this work, a wastewater HP system has been introduced and a model in Trnsys has been developed in order to optimize it from the system point of view. 26 cases have been analyzed in order to determine the optimal size of the binomial HP-DHW storage tank. The main conclusion extracted from the results are:

- The size of the peak demand is not enough in order to design a component. In fact, in a yearly profile DHW demand, not only the peaks but also their position as well as the number of peaks within a day need to be considered for an accurate sizing.
- In heat pumps, tank losses are translated to a more elevated temperature production, which increases the ambient losses of the tank and decreases the COP of heat pump. Thus, when designing, the heat pump secondary fluid temperatures need also to be considered. This effect is negligible in the studied cases but could be significant in other cases in which the tank size is smaller or when the DHW tanks are oversized resulting in an accumulation of water for a long time.
- The minimum HP size and maximum volume size is found with average water mass flow rate productions during the operating time.
- The proper sizing of the DHW storage tank allows the HP size to be independent from the DHW profile shape
- For a given HP size, the minimum DHW storage tank volume is mostly influenced by the shape of the demand profile.

A relationship among the HP-DHW storage tank sizes exists and the no consideration of that could result in significant different solutions. Further work must be done in order to investigate further this relation and to find an algebraic expression to allow general calculations.

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ACKNOWLEDGEMENTS

Part of the work presented was carried by Estefanía Hervás Blasco with the financial support of a PhD scholarship from the Spanish government SFPI1500 × 074478XV0 and part of the work by Javier Marchante with the finaltial support of the “Ministerio de Educación, Cultura y Deporte” inside the programme ‘Formación de Profesorado Universitario (FPU15/03476)’. The authors would like also to acknowledge the Spanish ‘MINISTERIO DE ECONOMIA Y COMPETITIVIDAD’, through the project "MAXIMIZACION DE LA EFICIENCIA Y MINIMIZACION DEL IMPACTO AMBIENTAL DE BOMBAS DE CALOR PARA LA DESCARBONIZACION DE LA CALEFACCION/ACS EN LOS EDIFICIOS DECONSUMO CASI NULO" with the reference ENE2017-83665-C2-1-P for the given support.