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Design of a grey water heat recovery system in order to satisfy the domestic hot water demand of a block of dwellings

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Abstract

Passive houses linked to more efficient heating and cooling technologies have been one of the focus in last years. However, to close the loop of the building sector, there is still one open source: wasted heat from grey water. This paper addresses the potentiality of the wasted heat from grey water to produce domestic hot water (DHW) based on a heat pump system. A heat pump designed specifically for that application, a heat recovery heat exchanger and two variable volume storages tanks compose the system. The main objective of this work is to determine the potential of recovering this waste heat source in order to minimize the house energy consumption. An optimization of the size of the different elements and of the operation algorithm of the system has been performed in order to minimize the CO2 emissions and evaluate the maximum potential of the proposed strategy. The potential of using this type of waste heat as a source for heat pump system is demonstrated and could imply a recovery of available energy of up to 60%.

Keywords: Energy efficiency; Heat Recovery; Heat Pump; Domestic Hot Water;

1. Introduction

In recent years, there has been a great effort in order to reduce the energy consumption in buildings. The main actions have been focused on both, the reduction of heating demand and on the improvement of the technologies used for heating and cooling ends. However, little attention has been paid to the reduction of the energy demand related to DHW production even though, in developed countries, accounts for approximately 15% [1].

Furthermore, 85-90% of the total energy dedicated to hot water production [2] is wasted to the ambient after its use and the recuperation of it has not been explored in depth.

Based on that, the use of high efficient technologies for water heating applications as well as the heat recuperation from warm wastewater can significantly contribute to the reduction of the energy consumption and the GHG emissions associated to the building sector. Heat pumps are the most suitable technology dealing with the mentioned two aspects: high efficiency and the use of medium-low temperature water flows as a heat source.

The main characteristic of this kind of systems are:

a. The heat sink has a high water temperature lift and a high demand variability.

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b. The heat source has slightly higher temperature than the water from the net (and stable through the year) and high variability.

In order to deal efficiently with the characteristics of the heat sink of this kind of system transcritical CO2 systems or subcritical with subcooling control systems has been used and usually they work against a tank which could absorb the variability. Regarding the other point, it is not so widely analysed in the litreature, heat pumps are able to work properly with the temperatures of the heat source and also a tank could respond to the variability of this source but based on the temperature level to include in the system a heat exchanger recuperator will increase the efficiency of the system. Considering all these factors, at this point, the most critical point about this part of the system is related with the amount of energy available and the optimum way to use it in order to satisfy the demand.

The control strategy plays a key role on the system efficiency. Most works dealing with HPs use pre-defined schedules function of electric tariffs and base their design on that, hiding the real potential of a HP system or even deteriorating the performance by simply avoiding energy aspects[3]. Furthermore, the solutions obtained in that way may be specific just for a specific case. For instance, in [4] the operation of the heat pump is directly driven by the off-peak electricity period or in [5] the majority of the production also takes place in these periods. In [6], the authors analyze under an energy and economic point of view the impact of the operation control of a HP-photovoltaic system concluding that the optimization of energy factors results in a degradation of the economic factor and viceversa. An approach to maximize the energy efficiency and then couple it with specific economic aspects may be more interesting.

The aim of this work is to analyze the influence of the available waste energy in the energy consumption of a DHW system based on heat pumps. To do so, a thermodynamic analysis of the most suitable system able to produce hot water depending on the heat source characteristics is done. As a proof of concept, 20 dwells have been used as an example to develop the proposed methodology. The study considers first an infinite availability of heat source. Thereafter, a finite but constant profile of grey water has been taken into account and finally, profiles based on the grey water produced by the dwells are studied and compared to previous cases.

The considered systems are composed of a heat exchanger regenerator, two water tanks and a heat pump using the control of subcooling to optimize the efficiency working with high water temperature lift in the condenser. The study includes the sizing of the different components (heat pump, recuperator, tanks) and the definition of the optimum control strategy of the system. The obtained results allow quantifying irreversibility added to the system by the use of low-grade heat sources, gives some guidance about its potential that could be used in other works and supplies an estimation about the expected differences in energy consumption associated to the system design and waste heat availability.

2. Methodology

2.1 Heat sink and heat source characterization

This study focuses on DHW production for residential sector. Thus, the heat sink is the end-user hot water demand. A yearly profile for 20 dwellings generated with the stochastic model, DHWcalc [7], has been used. The selected time step has been of 1 minute. This profile includes an estimation of socioeconomic factors and it has been validated with SynPro[8]. The profile is the same as the one used in [9]. The reader is referred to it for further details.

The daily DHW demand is 54.1 l. of water at 45°C per person and per day. This represents an annual average energy consumption of 576kWh (for a net water temperature of 10°C). That is, an average water consumption at 45°C of 105.5 litre per apartment and a total mean water consumption of 2110 litre/day (for 20 dwells).The profile for the water inlet temperature has been determined following the methodology proposed in [10] and used in [8] based on Eq. 1.

$$T_{net} = \overline{T_{amb}} - 3 \cdot \cos\left(\frac{2\pi}{365}\left(n_{day} - n_{days,offset}\right)\right) \quad (1)$$

Where $\overline{T_{amb}}$ is the mean ambient temperature (10°C), n_{day} is the day of the year and $n_{daus,offset}$ is the offset, set according to the coldest day of the year.

Regarding the heat source, the grey water production from 20 dwellings has been considered. Grey water includes all water consumptions in a house except that from toilets (black-water) collected before the general sewage system. Due to the scarce information about grey water in the litreature, the estimation of the profiles and its characteristics have been done based on the total average water consumption, the end-use, the typical temperatures according to its use, the characterization of the DHW load profile and data found in literature.

Germany has been considered as the reference country for the grey load profile used. Furthermore, as the consumption in this country is rather conservative compared to other developed countries, for the potential estimation of heat recovery, which will imply that the obtained results would be conservative. According to [11], the average drinking water consumption in Germany is 123 litre per day and person (240 litre per day and apartment). The final end-mix for the grey water is based on [12]: 15% to shower, 25% to bath, 30% to flush the toilet, 13% to the clothes washing machine, 7% to dishwasher, 6% to hand wash, cleaning and gardening and 4% destined to cook. That is, grey water represents 70% of the total drinking water consumption (168litre per day and apartment).

Furthermore, both streams, DHW and drinking consumption, are related in terms that all DHW mass flow would be part of the grey water. Hence, as the daily average DHW consumption per household is 105.5 litre at 45ºC, the rest would come from the other uses except, toilets.

On the one hand, the grey water from DHW water has been considered to follow the same profile as the DHW but one-minute delayed (time considered between the hot water consumption and its availability as a grey source). These flows have been increased with drinking water (net water) up to the user final temperature demanded (45 ºC).

On the other hand, a profile representing the use of clothes and dish washing machines has been generated with DHWcalc software. Average flow rates, frequency and temperatures have been estimated according to the work presented in [13] and the mentioned drink water consumption.

Table 1 collects the main inputs used in DHWcalc software for the characterization load profile of the clothes and dish machines. An average consumption of 960litre/day, 20 dwells with a daily probability function based on a step function for weekends and weekdays, a 120% probability weekday/weekend and seasonal variations are accounted by means of sinusoidal function have been considered.

Table 1: Drink water use in appliances that do not require DHW inputs for DHWcalc.

Draw-off type	End-use temperature [ºC]	Mass flow [lpm]	Duration [min]	Probability [%]
Dishwasher	65	4.8	1	11
Hot rinse	50	4.2	1.5	15
Cold rinse	45	3.6	1	9
Cloth washer	37	10.2	3	65

From the available data, the authors consider as good estimation the values of the hot water temperature used in the work presented in [13] which have been obtained from a wide literature review and experimental measurements. Table 2 collects the temperature of the end-user used in this work for both types of streams.

Regarding to the temperature of the grey water at the drain, a drop of 7K from the end-user temperature has been estimated regardless the nature of the consumption. This value is based on the most conservative study performed [14].

The grey water load profile is obtained aggregating the DHW profile with one-minute delay, the profiles of the clothes and dish washing machines with a thirty-minutes delay generated with DHWcalc and mixed with cold water until the end-use temperature for an annual time-frame and one-minute step time. An average daily grey water availability of 3360litre (168litre/apartment) and an average grey water temperature of 32.8ºC is obtained out of that mix.

2.2 Model description

Figure.1 shows a scheme of the main components, water flows and average temperatures of the system.

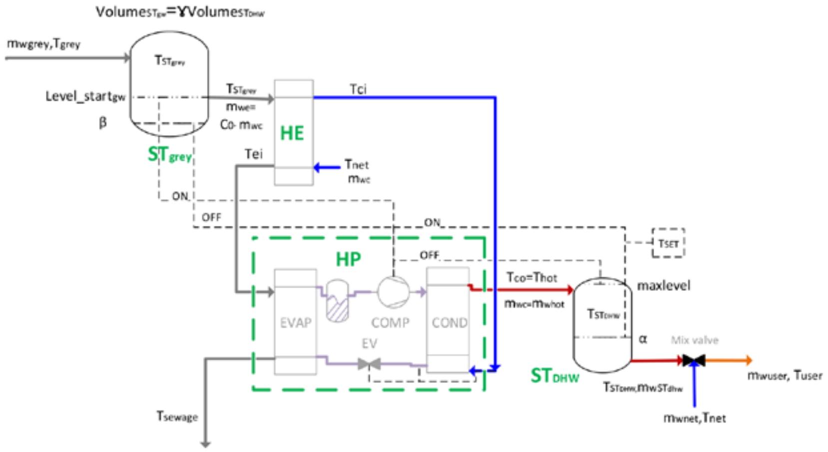

Figure.1: Lay-out of the system and average temperature conditions.

The main components of the system modelled are:

- Grey water storage tank (ST_{gw}): The variable volume storage tank modelled in Type 39 has been used. The size of the tank (Vol_{grey}) is one of the optimization parameters to minimize CO2 emissions. As conservative case, a geometric configuration that favours stratification has been used, that is H/D=4. The heat loss coefficient has been set to the one required by the Spanish legislation for DHW production, *RITE 07 IT 1.2.4.2.1.2,* that is 0.8W/m2K. An ambient temperature of 20ºC is set for all the simulations, as it is a typical value inside the houses through the year.
- Heat recovery heat exchanger (HE): Heat exchanger with an efficiency of 0.75 (type 5b). This heat exchanger will allow a first energy recovery.
- Water to water subcooled heat pump (SHP): This type contains a validated model of the subcooled heat pump [12].Due to its especial characteristics, a common HP type does not represent its behaviour properly and a new type was required. For further details about the developed type, the reader is referred to [15].
- DHW Storage tank (ST_{DHW}): For DHW Type 39 has also been used. As it is the case in $ST_{gw,}$ the size of the tank (Vol_{DHW}) is one of the optimization parameters to minimize emissions. The same insulation, geometry and characteristics used in the storage tank for grey water have been set in this case.
- Auxiliary water pumps and circuits: Types 742 with an efficiency of 0.3. Only the pressure drop of the heat exchangers were considered in order to evaluate their consumption.

Figure.2 represents the main inputs, outputs and optimization parameters of the model. In that scheme, scale is the size of the SHP, Volume is the size of the ST_{DHW}, γ indicates the proportion of the ST_{DHW} size and it is used for the ST_{gw} size ($Volume_{gw} = \gamma \cdot Volume_{DHW}$). α is the ST_{DHW} level when the heat pump switches on, Tset is the ST_{DHW} temperature, Tco is the condenser outlet temperature and C_0 is related to the grey water mass flow rate (evaporator water mass flow rate) as a proportional value of the condenser water mass flow rate.

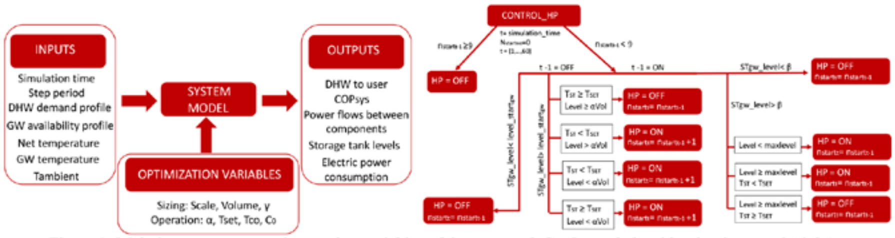

Figure.2: Main inputs, outputs and operation variables of the system (left). Control algorithm implemented (right)

The performance of the system (COP_{system}) is calculated according to Eq. 2

$$COP_{system} = Energy/Electric = \int_{t=0}^{t=simulationtime} (Q_{ST_{DHW\_out}})/(W_{c\_corr} + \sum W_{pumps}) \quad (2)$$

One should notice that the "useful energy" supplied by the system is the result of the heat exchanged in the HE and the heating capacity of the HP after the ST losses.

The scheme of the used control algorithm is presented in figure 5 (right) and it is based in the minimization of the time that the water is stored in the tank.In that figure *t* is the minute simulation time within each hour, T_{ST}, *Level*, α, *Vol*, T_{SET} and *maxlevel* refer to the DHW storage tank while subscript *gw* is used for conditions related to the grey water storage tank. It should be pointed out that once the HP is operating and while there is enough availability on the grey water storage tank, it keeps in the ON mode until the maximum level of the tank is reached or, in case it was already at that level, it keeps recirculating until the set point temperature (Tset) is reached. The used comfort criteria are based in two conditions, satisfy the demand 99% of the time and do not allow more than one-minute shortage at the same hour daily.

3. Performed Studies

Three cases based on the grey water conditions have been investigated and compared:

a) Infinite availability of grey water.
b) Finite availability of grey water and constant in time
c) Finite availability of grey water and no constant in time

According to [9], there is a set of system combination (size of the system componets and control) resulting in similar performances. Taking this point into account, the conditions b) and c) will be analysed in more detail for the solution corresponding to the smaller heat pump size (scale) and the solution with the smaller ST sizes (ST_{DHW}). Grey water energy available along the year is the same for the case 2 and 3 (the only change is when this energy is available). Table 2 shows the main inputs, variables used for limited m_{wgrey} availability based on the profiles of T_{net}, T_{grey} and m_{wgrey} presented in the methodology section.

Table 2: Main inputs used in each case

		T_{net} [ºC]	T_{gw} [ºC]	GW_{avail}	C_0 [-]
1	Infinite grey	10	33	∞	10
2a	Finite, $Scale_{min}$	10	33	Constant	2.27
2b	Finite, ST_{dhwmin}	10	33	Constant	2.27
3a	Design cond. $Scale_{min}$	7	25	Constant	2.33
3b	Design cond. ST_{dhwmin}	7	25	Constant	2.33
3c	Real cond. $Scale_{min}$	Profile	Profile	Profile	Opt.
3d	Real cond. ST_{dhwmin}	Profile	Profile	Profile	Opt.

a) Case 1: Infinite availability of grey water

This case will define the base case in order to evaluate the constrains imposed by limitations in the heat availability for the rest of the analysis. The methodology followed in [9] has been used. Notice that infinite availability of the heat source leads to the absence of the ST_{grey} and its derived variables.

Parametric studies have been done in order to obtain the map of possible solutions and the set of optimal combinations (heat pump size, Tank of DHW, alpha) that lead to minimum CO2 emissions satisfying the DHW demand under the comfort levels and operating constrains.

Figure 3 shows the parametric studies performed over the different design alternatives (heat pump size, storage tank size and control algorithm) for the available grey heat source (optimal m_{wevap}). This matrix comprises more than 4000 simulations

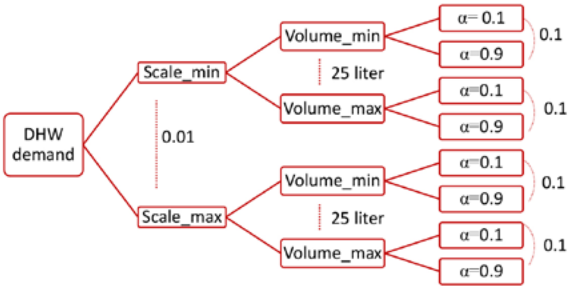

Figure 3: Parametric studies performed for available grey heat source based on variations of 0.01 in the scale of heating capacity, of 25litre in the ST_{DHW} tank and of 0.1 in α.

Where:

- *Scale* variation range: it has been expressed in terms of heating capacity (Q_{cond}) in the results section.
- *Volume* variation range: for each heating capacity, the maximum and minimum ST size that meet discomfort levels are investigated.
- *Alpha (α)* variation range: for each ST size, the variation of the control level in terms of a volume percentage.

b) Case 2: Finite availability of grey water and constant in time

The same parametric studies shown in Figure 3 have been performed. In order to compare this case with the case 1, two situations have been analysed quantitatively:

1. Case 2a: Solution with minimum heat pump size (scale factor).
2. Case 2b: Solution with minimum ST_{dhw}.

c) Case 3: Finite and not constant availability of grey water

Real applications introduce variability in three ways: time, temperature and quantity. These variables add complexity to the system and require the use of a ST_{gw}.

The main target of this study consists of analysing, on the one hand, the impact on efficiency of these limitations in the available energy compared to the previous cases and, on the other hand, the coupling of all the system components considering dynamic and real conditions from the system point of view. Hence, the use of a ST_{gw} and the definition of a proper operating strategy to integrate it in the system is necessary. In addition, this will help to get an estimation of the influence in the efficiency of the system design. Two subcases will be analysed in this part:

1. System design based on a constant profile of waste water

The size of the system is performed following the same methodology of case 2 but for T_{net}=7ºC and Tgrey=25ºC. These temperatures correspond to the worst expected conditions along the year. The available m_{gw} is the mean value of the grey water produced along the day.

The tandem HP-ST_{DHW} is sized according to these conditions. In this conditions, it is necessary to include in the design the ST_{gw} in order to accumulate the produced grey water when the system is not on. This component is dimensioned as: $Volume_{STgw}=\gamma\cdot Volume_{STDHW}$. Two solutions are analysed for this case:

Case 3a: Solution with minimum heat pump size (scale factor).
Case 3b: Solution with minimum ST_{dhw}.

2. System design based on a real profile of waste water

The system has been optimized in order to satisfy the real profiles of the wastewater and of the net water temperature. This optimization is based mainly in:

- C_0 control: This parameter is optimized when using the highest available m_{wgrey} To maximize its use, the control is based on the maximum available m_{wgrey}.

- α control: The minimum α capable to satisfy the demand is the one that ensures the shortest water stored time (for a given size of the components).

Finally, and following the same procedure as before, the two cases were analyzed:

Case 3.2.a: Minimum heating capacity
Case 3.2.b: Minimum ST_{dhw} .

4. Results

This section shows the results obtained from the previous cases. First, the feasible set of combinations are detailed by case. Second, the most representative results are collected in Table 4 in order to compare them. Third, a detailed analysis of the obtained results from CASE 3 is presented.

Case 1: Infinite availability of grey water

Figure 4 depicts the possible sizes combinations for the optimal α that meet the discomfort standards described in the methodology section. Figure 4a refers to the operating hours, Figure 4b to the COP of the system and Figure 4c to the associated CO2 emissions.

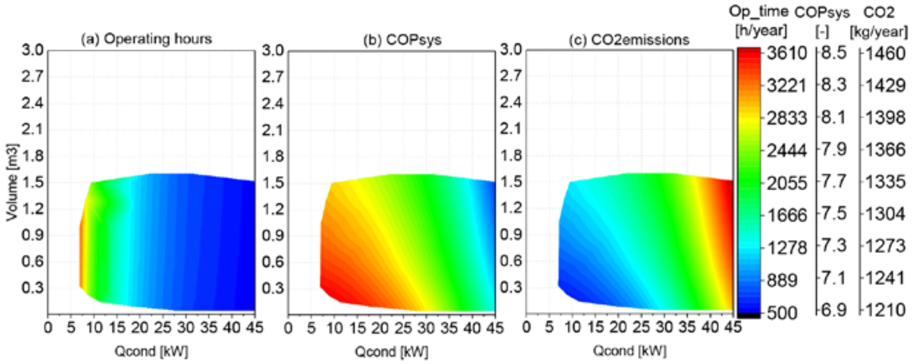

Figure 4: Annual operating hours, COP of the system and CO2 emissions associated to an infinite available grey water heat source and the optimal alpha.

According to Figure , low-temperature heat source recuperation has a great potential in DHW production applications. There is a wide range of combinations HP-ST_{DHW} that result in similar CO2 emissions (around 1230kg/year) and that are capable to operate under COPs up to 8.5 with operating hours around 2200 hours (6h/day). From all these combinations, the minimum CO2 emissions value is obtained for α=0.5, Scale=0.15 (heating capacity of 9.42Kw) and a ST_{DHW}=250litre.

To be able to compare directly results, that case has been taken as an example or base case out of all the possible best combinations. These results are presented in table 4.

Case 2: Finite availability of grey water

Figure 5 shows the possible ST-HP combinations for the optimal α that meet the discomfort standards described in the methodology section when limiting grey water to the considered availability. Figure 5a refers to the operating hours, Figure 5b to the COP of the system and Figure 5c to the associated CO2 emissions.

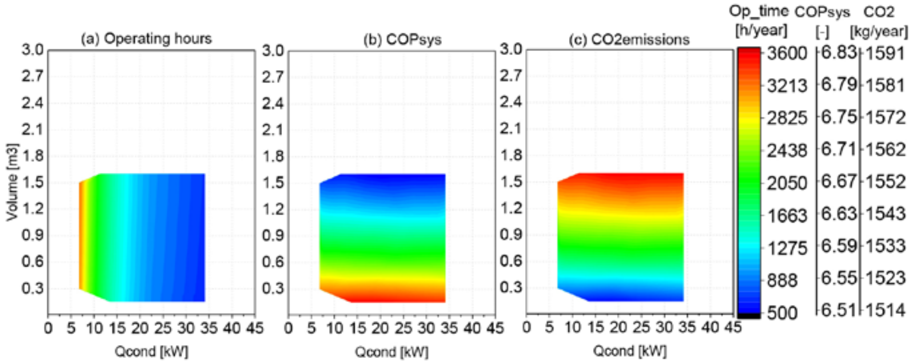

Figure 5: Annual operating hours, COP of the system and CO2 emissions associated to a finite available grey water heat source and the optimal alpha.

In this case, the reference combination obtained with optimal m_{wgrey} does not meet comfort standards. Hence, higher ST and/or heating capacities are required. Furthermore, the limitation of m_{wgrey}, lead to small COP variations with the increase of the heating capacity of the heat pump (for a given ST_{DHW} size). The ST_{DHW} size the most influent variable on the performance.

According to Figure and Figure 5, from the comparison of the optimal solutions in both systems (the combination with minimum CO2 strictly), the limitation of the available grey water results in a reduction in the COP of the system up to 20%.

In order to compare from a quantitative point of view the obtained results. Table 4 presents the numerical values for case 2a (solution with the minimum heat pump size) and case 2b (solution with the minimum ST size). In this table, it can be seen that for the case 2a the heating capacity is reduced due to a COP_{hp} loss and the solution results in higher ST_{DHW} as well as CO2 emissions. For the case 2b, the heating capacity required is significantly greater and 23% increase of CO2 emissions is obtained.

Case 3: Finite and variable availability of grey water

Similar results to the ones shown Figure 5 were obtained from the parametric studies performed in case 3 to design the components of the system. From all the possible combinations, two have been highlighted: the combination with minimum Scale (case 3. a) and the combination with minimums ST_{DHW} and ST_{gw} (case 3. b). The same situation is found once the system is adapted to the real profiles and results considering the adaptation to the profiles for the minimum HP size (case 3.c) and the minimum ST_{DHW} and ST_{gw} sizes (case 3.d) are highlighted Table 4 collects the most important results of each case.

Table 3: STgw-HP-STdhw optimal combinations for infinite availability of the heat source, finite availability but constant, and finite and variable availability.

		Scale [-]	Heating capacity [kW]	ST_{DHW} [l]	ST_{gw} [l]	α [-]	COPsys [-]	Annual Op.g hours [h]	Annual emissions [kgCO2]
1	Infinite grey	0.15	9.42	250	-	0.5	8.49	2310	1219.4
2a	Finite, $Scale_{min}$	0.15	6.9	300	-	0.9	6.85	3100	1510.9
2b	Finite, ST_{dhwmin}	0.2	9.08	250	-	0.9	6.8	2351	1522.6
3a	Design cond. $Scale_{min}$	0.15	6.06	500	1250	0.9	5.68	4261	1970.6
3b	Design cond. ST_{dhwmin}	0.25	10.09	350	875	0.9	5.73	2541	1959.6
3c	Real	0.15	6.81	500	1250	0.9	6.67	3175	1540.3

	cond. $Scale_{min}$								
3d	Real cond. ST_{dhwmin}	0.25	11.38	350	875	0.5	6.72	1890	1529.1

According to Table 3, the consideration of real profiles (demand, temperatures and grey water availability) with a design based on extreme constant conditions, cases 3.a-3.b leads to a solution with higher sizes of the main components and the performance of the system decreases in more than 30% compared to case 1 and 20 compared to case 2. However, once the design is dynamically adapted to the variable conditions (cases 3.c-3.d)., the loss of efficiency diminishes to 2% compared to Case 2. High values of optimal α allow the reduction of the ST_{gw} γ_{min} parameter, while low-medium values require the design condition of γ_{min}.

Figure 6 contains the main characteristics of the grey water heat source. Figure 6a represents the monthly grey water energy extracted by the HP (grey column) and by the HE (line-filled column), the grey energy available in light brown and the percentage of energy extracted from the total available. Figure 6b shows the temperature of the grey water at the outlet of the evaporator (grey water temperature to the sewage) through the year.

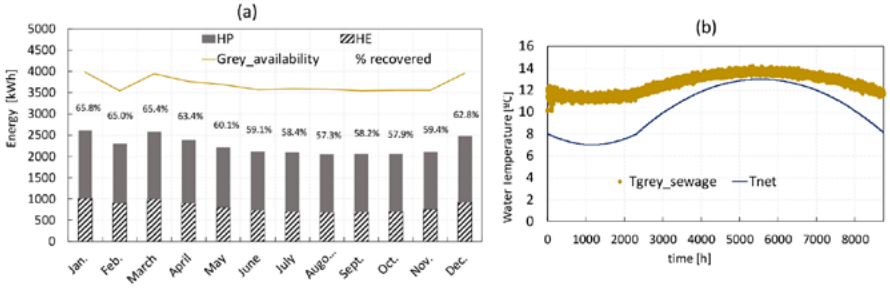

Figure 6: Monthly grey energy recovered and available and final annual grey water outlet temperature (to the sewage).

As it can be seen in Figure 6, a significant heat extraction is done by the HE with slightly seasonal fluctuations. From the available energy to extract (considering the minimum water temperature of the sewage as 2ºC), an average extraction of 60% has been enough for the DHW supply. In addition, figure 6b represents the net water temperature and the temperature of the grey water at the outlet of the SHP, it can be seen that always the Tgrey_sewage >Tnet, therefore the system is able to satisfy the DHW demand only with recovered energy from the dwellings, in addition figure 6b also shows that the energy recovery system is more effective during the colder months.

Results highlight the great potential of grey water heat recovery as a heat source for DHW production based on a HE (recuperator) and a HP.

5. Conclusions

In this work, the influence of having a limited (and variable) availability of heat source at a given temperature in order to satisfy the demand of DHW has been addressed. The obtained results have been systematically compared with the results obtained when this restriction is not present and an optimum system configuration (HE (recuperator)+SHP+STdhw+STgw) have been proposed.

This analysis has allowed estimating the variations in energy consumption that could be expected from different design criteria. Finally, a system in order to satisfy the DHW demand of 20 dwellings using their grey water production as a heat source has been analysed in detail.

Regarding to the obtained results, the main conclusions can be summarized as:

- A decrease of 20% in the efficiency could be derived when there is a limitation of the available grey water in terms of average quantity compared with a system in which that availability of heat source water is not limited.
- When there is a not constant availability of grey water, and the system is sized according to the most critical conditions, the energy efficiency of the system could be reduced up to 17%.
- In the previous situation, significantly larger sizes of the components are required in order to satisfy the user comfort levels (for instance, double ST_{DHW} capacities for the minimum HPsize).

- The systems with a variable grey water availability could increase significantly their efficiency if the design conditions are based on the real profiles instead of the most critical conditions. With that design criteria, the decrease on the performance is only 2% compared to the case with a constant availability of grey water (case 2).
- The system is can work only with energy recovered from the heat pump, and the advantage of this type of system is higher when the ambient temperatures are lower.

Finally, a great potential of grey water used as a heat source for DHW production based on SHP has been demonstrated. When the system is properly designed and adapted to real availability and demand profiles, it is able to supply the required energy for water heating purpose only using only the grey water produced by the dwelling with high efficiency. In fact, only with the extraction of 60% of the available energy all the production can be satisfied for the example analysed in this work and all the used energy is energy recovered from the grey water source. Comparing this case with the case in which this energy is extracted from a heat pump of the same characteristics but using the air as a heat source, the potential savings derived from using the grey water are higher than 40%.

Nomenclature

DHW: domestic hot water
ST: storage tank
HE: pre-heating heat exchanger (recuperator)
SHP: subcooled heat pump
Tei: water inlet temperature at the evaporator [ºC]
Teo: water outlet temperature at the evaporator [ºC]
Tci: water inlet temperature at the condenser [ºC]
Tco: water outlet temperature at the condenser [ºC]
Tnet: water mains/net temperature [ºC]
Tgrey: water heat recovery temperature [ºC]
Tsewage: grey water temperature after its recovery (to the sewage) [ºC]
T_{ST}: water stored temperature in the respective tank [ºC]
Thot= water temperature at the system conditions [ºC]
Tuser= water temperature supplied to the user [ºC]
Tdemanded=water demand temperature [ºC]
Tset= temperature control [ºC]
Tamb= ambient temperature [ºC]
Qcond=Heat pump heating capacity [kW]
Qevap=Heat Pump cooling capacity [kW]
COP_{hp}: Heat pump Coefficient of Performance, [-]
COP_{sys}: System Coefficient of Performance, [-]
COP_{Lorenz}: Lorenz Coefficient of Performance, [-]
m_{wgr}: grey water mass flow rate [kg/s]
$mw_{use}r$= water mass flow rate to the user [kg/s]
m_{wc}:condenser water mass flow rate [kg/s]
m_{we}:evaporator water mass flow rate [kg/s]
Wc: Heat pump electric consumption [kW]
Scale: Relative size of the heat pump compared to the reference value
Volume: capacity of the respective tank [litre]
ρ: Water density [kg/m3]
α: Control level rate in the DHW tank[-]
β: Control level rate in the grey water tank[-]
λ: Ratio between the hot water mass flow and the grey water mass flow [-]
γ: proportion of the DHW storage tank capacity [-]
C_0: proportion of the condenser water mass flow rate [-]
Subscripts
ST: storage tank
HP: Heat pump
gw: grey water
DHW: domestic hot water
hot: hot water (at production temperature, 64ºC)

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