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Closing the residential energy loop: grey-water heat recovery system for Domestic Hot Water production based on heat pumps

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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 as a heat source to produce domestic hot water (DHW) based on a heat pump system (HP). A heat pump optimized for these applications, a heat recovery heat exchanger and two variable volume storage tanks compose the system. The main objective of this work is to determine the potential recovery of the wasted heat in order to minimize the building energy consumption. Design guidelines of the components and the analysis of an optimum operation algorithm of the system have been performed in order to minimize CO2 emissions. In addition, an evaluation of the potential heat recovery of the wasted heat is included. As an example, that methodology has been applied to 20 dwellings. Based on that case, the obtained results demonstrate that by recovering 80% of the available recovery heat, the total demand of DHW is satisfied with high levels of comfort and efficiency.

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 [liter]

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)

ci: Condenser inlet

1. INTRODUCTION

Nowadays, global policies tend to move towards a more sustainable system with a more responsible use of energy. In 2014, the European Union set the goal of reducing greenhouse gas (GHG) emissions and improving the energy efficiency up to 40% and 27% respectively by 2030 [1]. Currently, the building sector accounts for nearly 40% of the annual GHG emissions [2] and for almost 27% of the final energy consumption.

Therefore, the reduction of the energy consumption and the improvement of the technologies used in this sector are necessary in order to reach the 2030 targets.

In recent years, a great effort has been made in order to reduce the energy consumption in buildings. The main actions have been focused on both the reduction of heating demand and the improvement of technologies used for heating and cooling purposes. However, little attention has been paid to the reduction of the energy demand related to domestic hot water (DHW) production even though, it accounts for approximately 15% in developed countries [3].

Furthermore, 85-90% of the total energy dedicated to hot water production [4] is wasted to the ambient after its use. Its heat recovery has been studied in literature from the point of view of both thermodynamic potential [5] and heat pumps [6].

Based on that, the use of high-efficient technologies for water heating applications as well as the heat recovery 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 for dealing with the two mentioned aspects: high efficiency and the use of medium-low temperature water flows as a heat source. In order to analyze the use of heat pumps in these application, the most common approaches from the system point of view are related to showing the reliability of the system or are bounded by economic factors, such as electric tariffs [7] or cost functions [8][9] associating the control and design of the whole system to these parameters. The main disadvantage of these kinds of approaches is related to the fact that the obtained results depend on socio-politic parameters that could change over time.

Furthermore, the solutions obtained with those approaches may be just for a specific case difficult to extrapolate to other situations. For instance, in [10] the operation of the heat pump is directly driven by the off-peak electricity period, in [11] the majority of the production also takes place in these periods or in [12] the authors analyze the impact of the operation control of a HP-photovoltaic system under an energy and economic point of view, concluding that the optimization of energy factors results in a degradation of the economic factors and vice versa.

Approaches dealing with the optimization of only the energy consumption although they can supply valuable information are not so common. The situation is even worse when looking for studies in which this optimization has been done based on components specifically designed for this type of application from the system point of view.

An approach based on the maximization of the recovery potential using heat pumps from a purely energy analysis must take into account not only the heat pumps, but also the systems where they are integrated and based on that the operation of the heat pump and the rest of the system must be adapted properly to the specific characteristics of the heat sinks and heat sources. Later on, these characteristics are going to be described more in depth.

a) Heat sink characteristics (DHW)

The main characteristics of DHW (heat sink) are high water temperature lifts and high demand variability:

- High water temperature lifts have been addressed by the use of transcritical cycles [13][14][15], mixtures [16][17][11] or, more recently, by the use of subcritical cycles with the application of high degrees of subcooling [18] [19] which can have substantial advantages compared to other heat pump systems in DHW production from heat recovery applications as it allows an improvement in the temperature match between the refrigerant and the secondary fluid deriving in a higher system efficiency.

High performances have been obtained with these solutions, in that line, the subcritical cycles with a subcooling control enhance the system efficiency at low and high temperature lifts [20][21][22][23][24], with reduced global system cost.

- To deal with high variability, the use of a variable speed compressors or storage tanks are required. When the variability is very high, the first solution penalizes HP efficiency as moving far away from the design condition could decrease the compressor efficiency and could be not enough to cover profiles with sharper peaks and intermittent production. In these cases, the second alternative, storage tanks, is commonly employed. A vast literature is available on optimization studies in terms of geometry and control of the tank, especially, coupled with CO2 HPs and solar systems where stratified tanks are desired [25][26][27][28]. More limited information is available about dealing with the operation and control of other types of tanks (such as variable volume or fully mixed) that are preferable under an energy point of view [29] [30][31][32] in some heat pump operating conditions.

b) *Heat source characteristics (wastewater)*

Building wastewater (grey water) is characterized by higher temperature than the ambient, stable through the year and with a high variability depending on the source of heat used:

- HPs are capable of operating under high efficiencies with medium-low temperatures within applications where there is no limitation of the water quantity

[30]. Examples of these are district heating [32][33][34], sewage water [35][36][26] or industrial heat recovery processes with high demand of refrigeration applications[37][38].

- The variability is directly linked to the variability observed in other sources like DHW. To ensure the availability of wastewater when it is required, the most common solution is to use storage tanks to collect wastewater when it is produced. HP performance remains high if a proper design and isolation of the tank is used [6][7][24] [39][40].
- The use of grey water from the building itself allows to have higher temperatures of the heat source than other sources like, for instance, sewage water. However, the availability of grey water produced by a building is limited. Thus, if this amount is small compared to the demand of heat, the temperature lift at the evaporator could increase so much that the resulting mean temperature in the evaporator secondary fluid could be lower than that obtained using other sources like seawage water, resulting in a decrease of the HP performance. Most works done in energy recovery from grey water are focused only on the direct recovery of part of the heat available in the grey water using just a heat exchanger (mainly water from showers) [5][40][41][42][43][44][45]. However, these kinds of systems lose an important part of the wasted energy potential and they are not capable of satisfying all the DHW demand. There are some works that uses heat pumps to supply the DHW demand based on energy recovery from the grey water available in the building, but they usually limit their analysis to act over the control/size of the system [46] but they do not deal with the adaptation of the heat pump and other components to the system characteristics in such a way that they lose part of the total potential of the system.

To maximize the efficiency of this kind of application, the recuperation system must be adapted to the specific characteristics of the heat sink and the heat source. This adaptation must include the heat pump but also the rest of the system components, the topology of the system and the control algorithm coordinating the design and operation of the whole installation in order to maximize the exergetic potential of the grey water. This kind of approach has not been totally assessed in most of the works available in the open literature like [8] [40][45][47][48][49].

Work and contribution of this paper

The aim of this work is to analyze the potential of the grey water produced by a dwelling in order to minimize the CO2 emissions associated to DHW production in the residential sector. To do so, the system described in [50] has been used. The configuration consists of a primary recovery heat exchanger, a heat pump prototype specially designed to maximize the COP of the whole system for this application (see [22] to find a more detailed description of its characteristics, this heat pump will be called subcooled heat pump (SHP)) and two variable volume storage tanks. This configuration is considered as the one which allows a higher energy efficiency potential.

The dynamic behavior of the system has been reproduced implementing a TRNSYS [51] model.

As a proof of concept, 20 dwellings have been used as an example to develop the proposed design. In order to perform a deeper analysis of the influence of the heat source in this kind of system, the study considers first an unlimited availability of the heat source. Thereafter, a limited but constant profile of grey water has been taken into account and finally, profiles based on the grey water used in the dwellings are studied and compared to the previous cases.

Based on this analysis, a highly efficient system in order to satisfy a DHW demand in the residential sector by the recovery of the heat from wastewater (grey water) has been determined. The study includes the sizing of the different components (heat pump, recuperator heat exchanger, tanks) and the definition of the optimum control strategy. The obtained results allow quantifying irreversibility added to the system by the use of variable low-grade heat sources. It also gives some guidance about its potential and supplies an estimation about the expected differences in energy consumption associated to the system design and wastewater heat availability.

2. METHODOLOGY

2.1. Heat sink characterization

This study focuses on DHW production for the 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 [52], has been used. A time step of 1 minute has been selected. This profile includes an estimation of socioeconomic factors and it has been validated with SynPro[53]. The profile is the same as the one used in [30]. The reader is referred to it for further details.

The daily DHW demand is 54.1 l. of water at 45ºC per person and per day. This represents an annual average energy consumption of 804 kWh (for a net water temperature of 10ºC). That is, an average water consumption at 45ºC of 105.5 liter per apartment and a total mean water consumption of 2110l/day (for 20 dwellings).

The consideration of a constant net water temperature is a good estimation for sizing or general purposes. However, seasonal effects and the variation of the net water temperature needs to be considered for a more detailed analysis. In fact, its fluctuation (mainly seasonal) can have an impact on the energy demanded up to 10% depending on the location [54]. In this work the profile for the water temperature from the net has been determined following the methodology proposed in [54] and used in [53] based on Eq. 1.

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

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

2.2.Heat source characterization

Decentralized grey water from 20 dwellings has been considered as a heat source. 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 literature, 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 the literature.

Germany has been considered as the reference country for the grey load profile used. According to [55], the average drinking water consumption in Germany is 123 liter per day and per person (240 liter per day and per apartment). The final end-mix for the grey water is based on [56]: 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 (168 liter per day and per apartment).

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). It is convenient to point out that DHW is going to be produced at 60ºC (*Legionella* regulation) but its end use is at 45ºC. In order to reduce the water temperature, some additional drinking water will be mixed with the DHW produced.

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 [40] and the drinking water consumption mentioned.

Table 1 summarizes the main inputs used in DHWcalc software for the characterization load profile of the clothes and dish washing machines. An average consumption of 960liter/day, for 20 dwellings 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: Drinking 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

The literature regarding to the temperature at the drain of each type of flow rate is also very limited.

From the available data, the authors consider as good estimation the values of the hot water temperature used in the work presented in [40] which have been obtained from a wide literature review and experimental measurements. Table 2 collects the water temperature of the end-user used in this work for both types of streams.

Regarding 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 [11].

Table 2 shows the temperatures at the end-use and at the drain considered in this study.

Table 2: End-use water temperatures and drain temperatures of the different streams considered.

Draw-off type	End-use temperature [ºC]	Drain temperature [ºC]
Handwashing	38	31
Shower	40	33
Bathtub	40	33
Cooking/cleaning	45	38
Washing machine	37	30
Dishwasher	53	46

The grey water load profile is obtained by 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 3360 liter (168 liter per apartment) and an average grey water temperature of 32.8ºC are obtained out of that mix.

Figure.1 depicts the daily mean temperature of the grey water. Notice that the use of mean temperatures for a daily scale hints the real temperatures used in each minute.

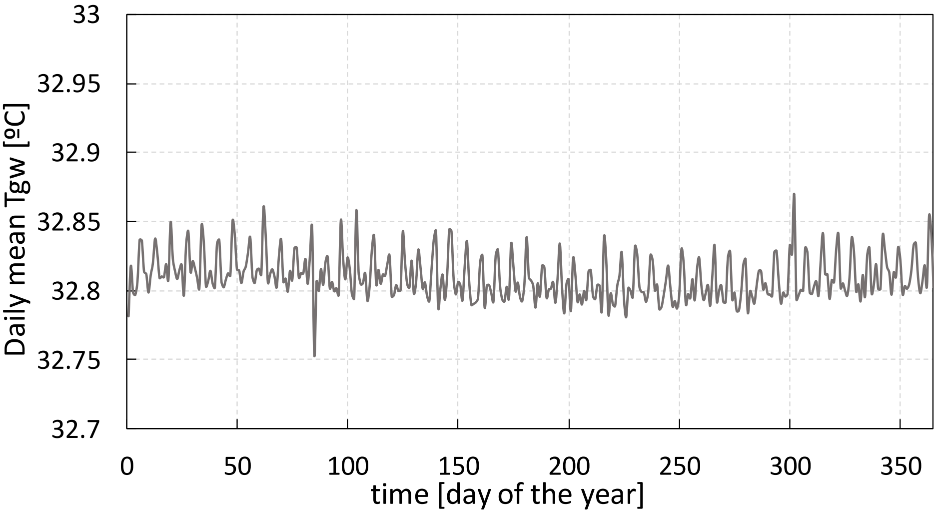

Figure.1: Daily mean grey water temperature over a year

Figure.2 represents the DHW demand load at 45ºC and the grey water available profile for 20 dwellings obtained using the described methodology. Water mass flow rates are expressed at a daily scale. However, it is important to remark that the use of a minute time scale when dealing with these type of profiles based on short periods and high variability demands is strongly recommended [57] and it has been the time step selected in order to perform all the simulations of this work.

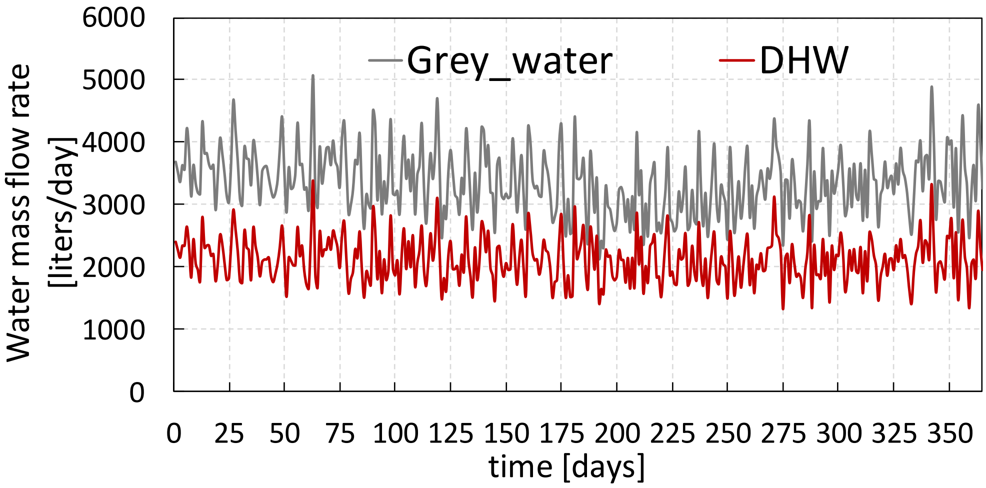

Figure.2: DHW and grey water daily- profiles for a 20 dwellings DHW consumption at 45ºC and Tnet 10ºC

2.3.Model description

Figure.3 shows a scheme of the main components, water flows and average temperatures of the system. The system configuration has been selected in order to maximize the efficiency in such a way that the energy recovery from the grey water is performed in two steps: first, with a heat exchanger (recuperator) and later on the rest of the energy is extracted using the SHP. This heat pump allows working with a good performance using a variable volume water storage tank for the DHW in such a way that the water accumulated in the tank does not need a reheat up allowing the tank to have only one inlet and one outlet.

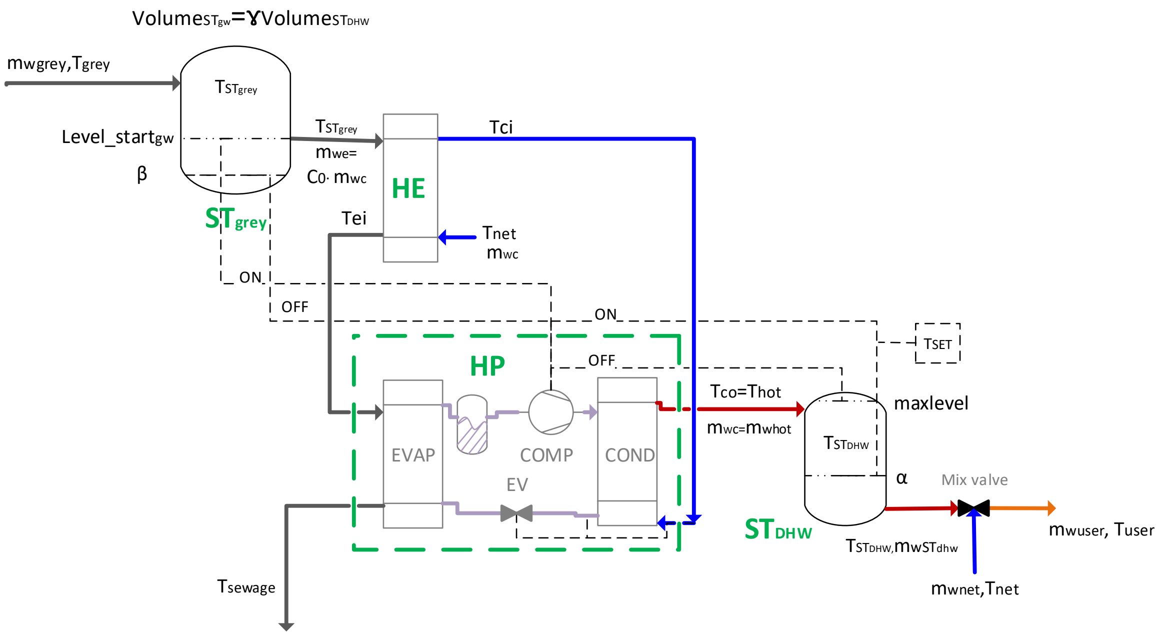

Figure.3: Lay-out of the system and average temperature conditions.

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 favors stratification has been used, that is H/D=4. The heat loss coefficient has been set to that 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 throughout 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 [19].Due to its especial characteristics, a common HP type does not represent its behavior properly and a new type was required. For further details about the developed type, the reader is referred to [30].

Figure.4 shows the main inputs and outputs of the HP type.

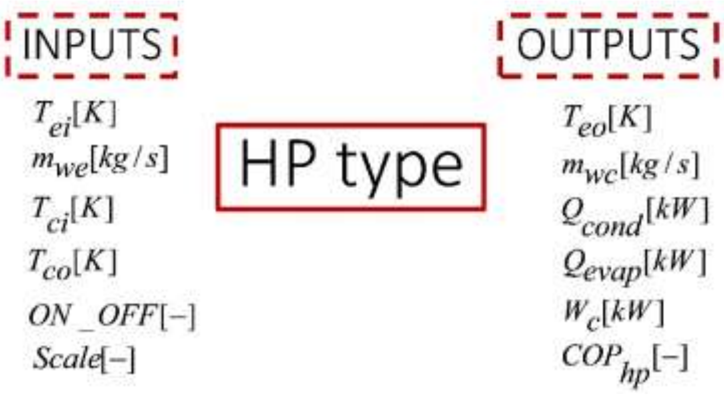

Figure.4: Inputs and outputs of the HP type

-DHW Storage tank (ST_{DHW}): For DHW Type 39 has also been used. As is the case for $ST_{gw,}$ 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 was considered in order to evaluate their consumption.

The simulations use a time step of 1 minute (as a consequence of the profile characteristics, longer time steps could due to the not proper sizing of the system) and include 1-year simulation period.

Figure.5 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.

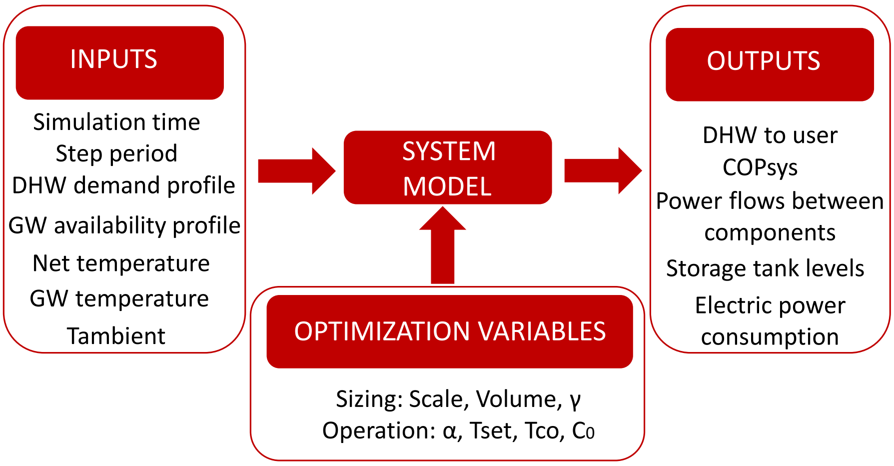

Figure.5: Main inputs, outputs and operation variables of the system.

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

$$COP_{sys} = Energy/Electric =$$

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

Where $Q_{ST_{DHW\_out}}$ (kW) is heat leaving the ST$_{\mathrm{DHW}}$, W_{c_corr} (kW) is the compressor consumption and W_{pumps} (kW) the auxiliary water pumps consumption.

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.

- *Control of the system*

As mentioned in [23], the main irreversibility is introduced by the ST. In this case, since there are two storage tanks, the operation control in order to minimize irreversibility (maximize efficiency) may rely on both components.

The ST$_{\mathrm{DHW}}$ temperature is higher than that in the ST$_{\mathrm{gw}}$ resulting in higher losses. That is, the control is based on the minimization of the time that the water is stored in the ST$_{\mathrm{DHW}}$.

Hence, the STgw should have enough water in order to allow the system to operate. Based on this, the control algorithm is based in the following points:

- Switching on the HP when a minimum level of water is reached in the ST_{DHW} (α, the optimization parameter) or when T_{STDHW} is lower than a predefined $T_{SET.}$ In addition, a maximum number of HP 9 starts of the HP allowed within one hour to ensure the HP durability has been implemented.

- Once the heat pump is running it stops when the water in the ST_{DHW} reaches a predefined level (maxlevel).
- In order to not incur more than 9 starts per hour, to soften the peaks and to ensure at least 30 minutes of the heat pump working continuously, a minimum level of the grey water in its tank has been set according to Eq. 3. to start up the heat pump:

$$level\_start_{gw} = {30 \cdot m_{w\_evap}}/{\rho_w} = {30 \cdot C_0 \cdot m_{w\_cond}}/{\rho_w} \tag{3}$$

where ρ_w is the water density (considered 1000 kg/m3). Notice that in this case, the initial volume is set to this level and that the one-minute scale allows introducing this type of control without significantly penalizing the ST size.

- A minimum level of the ST_{gw} to guarantee the production is required, and if the level in the tank is lower than this value the HP will be switched off. Therefore, the minimum volume of this tank will be limited by the production of grey water in one time-step. The safety coefficient of 3 has been employed. Eq. 4 shows the minimum volume of the ST_{gw}.

$$\beta = {3 \cdot m_{w\_evap}}/{\rho_w} = {3 \cdot C_0 \cdot m_{w\_cond}}/{\rho_w} \tag{4}$$

Therefore, the control of the heat pump is based on the tank level and temperature of the water within the ST_{DHW} (α, T_{STDHW}) and the availability of a minimum water volume to run the heat pump ($level\_start_{gw}$) and a minimum level (β) in the ST_{gw}.

Figure 6. shows the scheme of the control strategy implemented. In the 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 the 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 comfort criteria used are based on two conditions, satisfy the demand 99% of the time and do not allow more than one-minute shortage at the same hour daily (discomfort standards considered in the work). The second condition is added in order to consider the user satisfaction characteristics of this type of hot water demand.

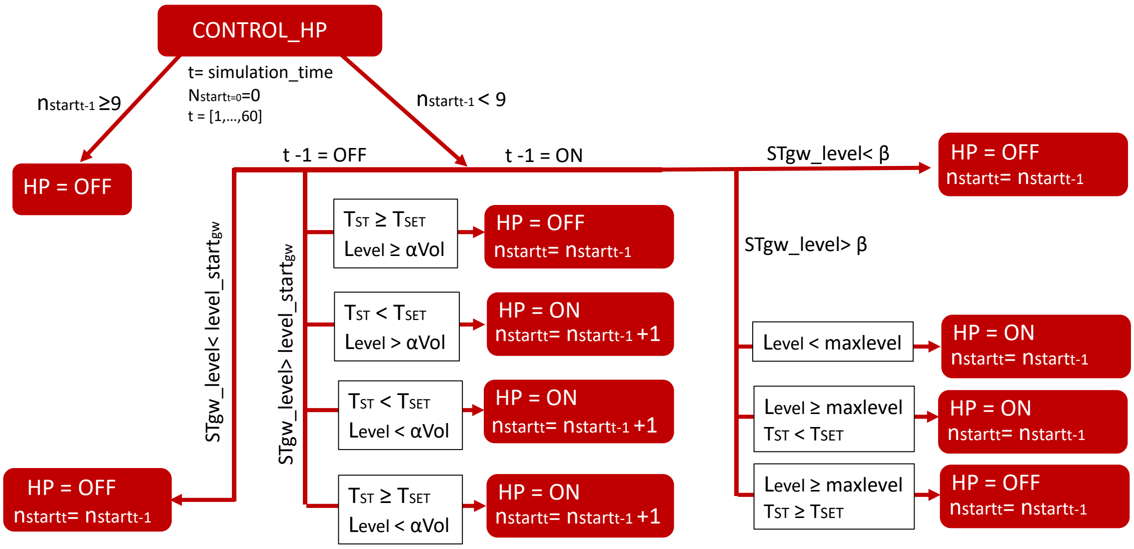

Figure 6: System control strategy implemented each hour of the simulation time. Subscript gw refers to grey water storage tank and no subscript is used for the DHW storage tank.

3. Grey water heat recovery potential

Before going into detail with the presentation of the studied cases, it is convenient to show a theoretical analysis of the grey water potential. This analysis would help the user to better understand the obtained results and to give some general guidelines on how to extend them to other situations.

In this work, the energy available for recovery is going to be considered as the energy that can be extracted from the grey water until it reaches the temperature of the water from the net. However, the water temperature can be reduced up yo 0ºC in case that this energy was necessary to satisfy the demand (for instance 2ºC for safety). In a more precise way, only the energy extracted from the grey water until it reaches a value equal to tap water can be considered as recovered energy. However, the authors have considered that clean water cannot be used as a heat source and based on that, the potential use of grey water as a heat source has been considered until it is exhausted.

Eq. 5 shows the heat recovery capacity from the grey water in terms of energy.

$$Q_{grey} = m_{w\_grey} \cdot cp \cdot (T_{grey} - T_{sewage}) \qquad (5)$$

where T_{grey} is the grey water temperature, T_{sewage} the temperature at which the water is thrown to the sewage and m_{wgr} is the grey water mass flow rate.

DHW flow rate is the main contribution to the grey water production. In fact, in this work 63% of the grey water comes from DHW appliances independently of the external conditions. Therefore, the available grey water mass flow rate can be related to the hot water consumption at 45ºC according to Eq. 6.

$$m_{w\_gr} \approx (1/0.63) \cdot m_{w\_user} \qquad (6)$$

Furthermore, according to the first law of thermodynamics, the energy required by the user should equal the energy stored in the ST_{DHW} as it is described in Eq. 7.

$$Q_{user} = m_{w\_user} \cdot cp \cdot (T_{user} - T_{net}) = m_{w\_\mathrm{hot}} \cdot cp \cdot (T_{ST_{DHW}} - T_{net}) \qquad (7)$$

Assuming a constant heating capacity of the water, the ratio of Eq. 8 is obtained.

$$\frac{m_{w\_user}}{m_{w\_\mathrm{hot}}} = \frac{(T_{ST_{DHW}} - T_{net})}{(T_{user} - T_{net})} \approx \frac{0.63 \cdot m_{w\_grey}}{m_{w\_\mathrm{hot}}} \qquad (8)$$

In general, the grey water mass flow rate can be expressed as a proportion of DHW shown in Eq.9.

$$m_{w\_grey} \approx \lambda \frac{(T_{ST_{DHW}} - T_{net})}{(T_{user} - T_{net})} \cdot m_{w\_\mathrm{hot}} = C_0 \cdot m_{w\_\mathrm{hot}} \qquad (9)$$

where for this particular case $\lambda = 1/0.63$

Ideal heat recovery with a standalone heat pump

The 2nd law of thermodynamics gives a restriction in the amount of heat that can be pumped from a heat source at a temperature T1 to a hot sink at a temperature T2 where T2>T1. Based on that limit, the limits of a heating process are set by the condition $Q_{heating}=Q_{recovered} + W_{cl}$ where W_{cl} is the minimum work required calculated using as a reference the ideal Lorenz cycle (this cycle is selected as a reference because of the heat source and sink can change their temperatures). W_{cl} would be 0 only if the thermal levels of the sink and the source allow the direct heat transfer but not in general.

From that expression, the ideal limits of maximum recovery, C_{0i}, are obtained according to Eq. 10.

$$C_{0i} = \frac{(T_{hot}-T_{net})}{(T_{grey}-T_{sewage})}\left(1-\frac{1}{COP_{Lorenz}}\right) \qquad (10)$$

where COP_{lorenz} is the Coefficient of Performance for the Lorenz cycle, which limits the maximum efficiency of the heating process considered [58] and is given by Eq. (11).

$$COP_{Lorenz} = \frac{1}{1-\overline{T_C}/\overline{T_H}} \qquad (11)$$

where $\overline{T_H}$ and $\overline{T_C}$ are the entropy averaged temperatures. For a constant capacitance and pressure process, the temperatures can be written as in Eq. 12and Eq. 13.

$$\overline{T_H} = \frac{T_{hot}-T_{net}}{ln({}^{T_{hot}}/_{T_{net}})} \qquad (12)$$

$$\overline{T_C} = \frac{T_{grey}-T_{sewage}}{ln({}^{T_{grey}}/_{T_{sewage}})} \qquad (13)$$

Where T_{hot} is the hot water temperature required in the heating process, (64ºC in this case).

These would be the theoretical ideal limits based on the second law of thermodynamics. C_{0i} represents the minimum ratio between m_{w_grey} and m_{w_hot} in order to be able to satisfy the hot water demand with energy recovered from the grey water. Notice that from the recovery point of view it is convenient to increase as much as possible the m_{wgr}

as higher values of it result in higher values of $\overline{T_C}$. From this analysis, ideally, if $C_0 \geq C_{0i}$, then all the water heating can be satisfied with energy recovered from the grey source and if C_0 is $< C_{0i}$ then in order to satisfy the demand part of the energy must be generated by other alternatives.

Nevertheless, once we define the heat pump that is going to be used to recover the waste energy, the COP of the system would be lower, and the energy balance can be expressed as $Q_{heating}=Q_{recovered} + W_{cl}+W_{ci}$. where W_{ci} is the additional heating that is introduced by irreversibility, and it is not the result of any thermodynamic heat pumped but it is just heat produced and added to the system (or it can be seen as a heat produced with a COP=1). It can be calculated as:

$$W_{ci} = \left(\frac{1}{COP_{HP}} - \frac{1}{COP_{Lorenz}}\right) Q_{heating}$$

It is suitable to generalize the concept of $Q_{recovered}$ to $Q'_{recovered}$ where $Q'_{recovered}$= Qrecovered + W_{cl} as W_{cl} is intrinsically bounded to the heat recovery process itself

Finally, the real heat recovery limit would be given by C_{0r}:

$$C_{0r} = C_{0i} \frac{\left(1-\frac{1}{COP_{HP}}\right)}{\left(1-\frac{1}{COP_{Lorenz}}\right)} \qquad (14)$$

where COP_{HP} is the COP of the heat pump. In the real situation the limiting condition will be $\underline{C_0 \geq C_{0r},}$ which is less restrictive and if the value C_0 is lower than that, there will be not possible to satisfy all the demand with the available water.

Based on the values of these C parameters a design criterion in order to determine the mass flow of grey water for the different cases has been followed. The criterion has been assumed that the water temperature difference in the evaporator is of 4.5 K and based on that the optimum mass flow depending on the SHP has been selected assuming the condition $C_0=C_{0r}$. A deeper explanation about the followed procedure can be found in the appendix.

Optimum heat recovery based on heat pump systems

Until this point, the potential of heat recovery has been analyzed from the point of view of the 1st principle (direct recovery) and of the 2nd principle (pumping recovery). However, the most common situation is to have thermal levels which allows an initial a direct heat recovery up to certain temperature level and later on a pumping heat recovery must be applied to satisfy the demand requirements. Hence, the most efficient configuration in this type of application is to install a heat exchanger + heat pump.

In order to gain insight into the order of magnitude of the relative importance of each component and obtain a first estimation of the potential energy savings, for the application under study, the percentage of heat produced by each component has been evaluated.

The heat recovery potential of the HE can be obtained by:

$$Q_{\mathrm{h}eating\_from\_rec}[\%] = \frac{m_{w\_\mathrm{hot}} \cdot cp \cdot (T_{ci} - T_{net})}{m_{w\_\mathrm{hot}} \cdot cp \cdot (T_{\mathrm{hot}} - T_{net})} = \frac{(T_{grey} - 5 - T_{net})}{(64 - T_{net})} \tag{15}$$

where T_{ci} is the inlet water temperature at the condenser, which has been obtained from the design assumption of 5K as the temperature approach (temperature difference between the grey water temperature and the cold-water outlet temperature).

In a heat exchanger with a temperature approach of 5K, Figure 7 depicts the maximum percentage of the energy supplied by the HE in order to heat a water stream from T_{net} to 64ºC from the recovery of a heat source at T_{grey} assuming a temperature difference of 5 K.

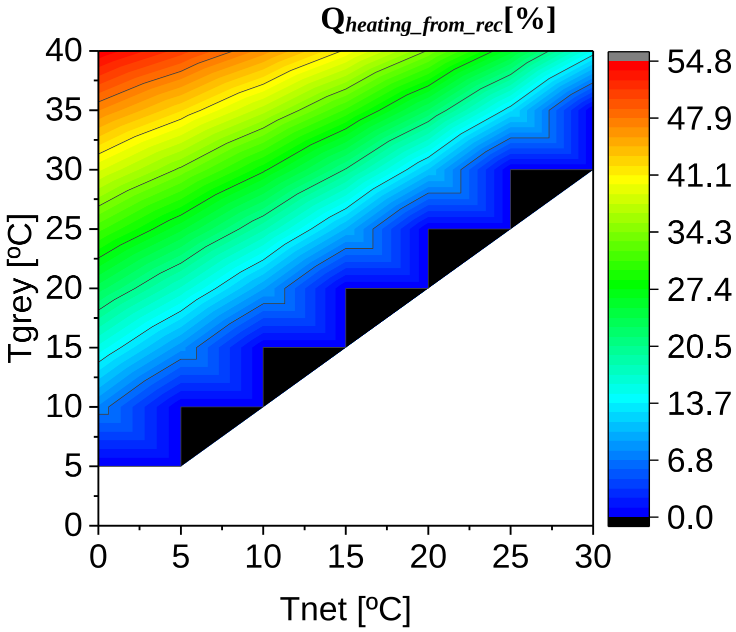

Figure 7: Maximum % of demand energy recuperated from the available grey water in the HE

According to Figure 7, the pre-heater HE represents a significant portion of total energy supplied to the system. For instance, for an average condition of T_{net}=10ºC and T_{grey}=33ºC, the energy demanded that can be obtained from the HE is 33%.

4. PERFORMED STUDY

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

Case 1 Infinite availability of grey water.

Case 2 Finite availability of grey water and constant in time

Case 3 Finite availability of grey water and no constant in time

According to [23], there is a set of system combination (size of the system components) resulting in similar performances. Therefore, among the different possible configurations, for the case 2 and 3, the solutions corresponding to the smaller heat pump size (scale) and the solution with the smaller ST sizes (ST_{DHW}) will be analyzed in more detail. The grey water amount available along the year and its mean temperature is considered the same for Case 2 and 3 but in Case 2 the grey water is distributed uniformly for all the hours of the year and has a constant temperature, meanwhile in Case 3 it is distributed according the profiles defined in Section 2. Table 3 shows the main inputs for the three cases, the variables used for limited m_{wgr} availability are based on the profiles of T_{net}, T_{grey} and m_{wgr} presented in the methodology section.

Case 1: Infinite availability of grey water

This case will define the base case in order to evaluate the constrains imposed by limitations of the heat availability for the rest of the analysis. The methodology followed in [23] has been used. Notice that infinite availability of the heat source leads to the absence of the ST_{grey} and its derived variables.

The greywater mass flow rate (m_{wgr}) used has been calculated according to the methodology of the previous section. Considering mean water temperatures of: T_{grey}=33ºC and T_{net}=10ºC, COP_{hp} is 5.96 (T_{co} =64ºC), $C_0=\infty$ (Eq. 9), C_{0i}=10.4 (eq. 10) and C_{0r}= 8.9 (eq. 14). The condition ($C_0>C_{0i}>C_{0r}$) is what indicates enough availability and C_0 is adjusted to 8.9 in order to have a grey water temperature lift of 4.5 K at the evaporator.

With these definitions for m_{gw} , parametric studies have been done in order to obtain the map of possible solutions and the set of optimal combinations (heat pump size, DHW tank size and control parameter α) that lead to minimum CO2 emissions satisfying the DHW demand under the comfort levels and operating constraints required.

Figure 9 shows the parametric studies performed over the different design alternatives (heat pump size, storage tank size and control algorithm) for the grey heat source available (optimal m_{wevap}). This matrix comprises more than 4000 simulations.

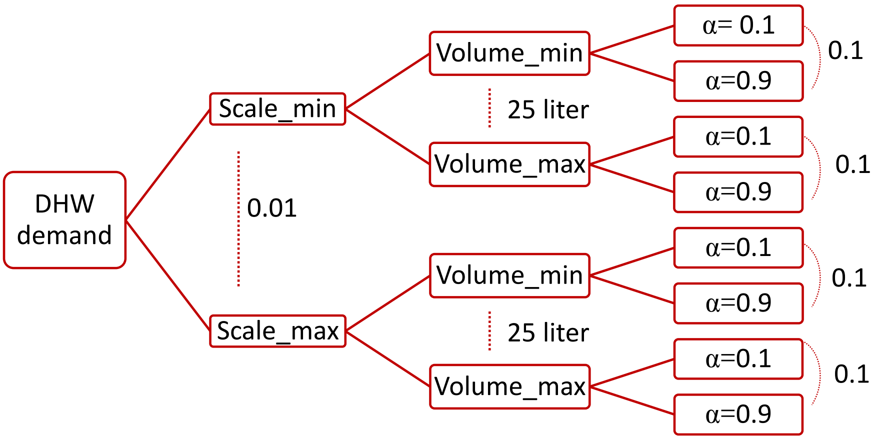

Figure 8: Parametric studies performed for available grey heat source based on variations of 0.01 in the scale of heating capacity, of 25liter in the ST_{DHW} tank and of 0.1 in α.

In the figure 8:

- *Scale* variation range: it has been expressed in terms of heating capacity (Q_{cond}) in the results section. It ranges from the minimum size that meets discomfort requirements to the size that corresponds to a minimum of 1.5 hour per day operating time. In 0.01 steps.
- *Volume* variation range: for each heating capacity, the maximum and minimum ST sizes that meet discomfort levels are investigated. In 25 liter steps.
- *Alpha (α)* variation range: for each ST size, the variation of the control level in terms of a volume percentage, changes from 0.1 to 0.9. In 0.1 steps.

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

In this case, the limitation of the grey water availability has been selected to the mean average ratio of the mass flow given for the used profiles (described in section 2) $m_{wgr}/m_{whot}=C_0=2.27$, the minimum value of $C_{0i}=1.63$ and $C_{0r}=1.45$. These values are obtained for the condition in which the evaporator water outlet temperature is 2ºC. The mean net water temperature, $T_{net}=10$ºC and the mean grey water temperature $T_{gw}=33$ºC and calculated in the same way as in the previous case. In this case, the situation is that $C_0>C_{0imin}>C_{0rmin}$. Hence, there should be enough energy from grey water to satisfy the DHW demand.

The same parametric studies shown in Figure 8 have been performed.

In order to compare this case with the Case 1, two situations have been analyzed quantitatively:

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

- **Case 3: Finite and not constant availability of grey water**

Real applications introduce variability in the grey water production in three ways: time, temperature and quantity. This situation adds complexity to the system and require the introduction of a new element, the ST_{gw}.

The main target of this study is, on the one hand, to define the coupling of all the system components considering dynamic and real conditions from the system point of view and, on the other hand, to determine the impact on the system efficiency of these restrictions in the available energy compared to the previous cases.

The analysis of this case is going to be done in two steps:

1. *System design based on a constant profile of wastewater*

The system designed for the Case 2 have the same amount of grey water than the Case 3, but as a consequence of the variability in time introduced in the case 3, the system designed in the case 2 is not able to satisfy the DHW demand under the variable m_{gw} conditions of the Case 3. Hence, in the Case 3 the system must be redesigned.

The same methodology of case 2 has been followed but in this case the design temperatures correspond to the worst conditions expected throughout the year (T_{net}=7ºC and Tgrey=25ºC). The available m_{gw} is the mean value of the grey water produced throughout the year. The tandem HP-ST_{DHW} is sized according to these conditions. In addition, for this case, it is necessary to include in the design the ST_{gw} in order to respond to the variable m_{wgr} production. This component is sized as: $Volume_{STgw}=\gamma\cdot Volume_{STDHW}$.

The worst condition for $Volume_{STgw}$ is obtained with highest minimum level of ST_{gw} and lowest minimum level of ST_{DHW}. In this case, the critical conditions to size the ST_{gw} are: $C_0=2.33$, $\alpha=0$ and a 30 min of availability according to Eq. 9. That is, $\gamma=2.5$.

As in the case 2, two solutions are analyzed for this case:

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

2 *System design based on a real profile of wastewater (variable availability of wastewater)*

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

- C_0 control:

  Heating processes based on finite sinks/sources have better performance with greater heat source mass flow rates (m_{wgr}) when ($C_0>C_{0i}>C_{0r}$) as is the case. Thus, C_0 is optimized in order to maximize the use of m_{wgr} in each working condition.

- α control:

  The minimum α capable of satisfying the demand is the one that ensures that the water remains in the DHW tank for the shortest time. Thus, this value has been determined out of simulation parametric cases for the components size and α.

Following the same procedure as before, the same two situations were analyzed:

1 Case 3c: Minimum heating capacity.

2 Case 3d: Minimum ST_{dhw} .

Table 3: Main inputs used for the design of the system in each case. Grey cases correspond to cases where the conditions were used for the design/size of the different components but do not correspond with a real situation under analysis.

	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.

Therefore, in order to analyse the Case 3 with limited and variable supply of grey water, case 3a and case 3b has been used in order to size the HP-ST_{DHW} and later on the obtained values has been used in order to properly analyse the the system in Cases 3c 3d.

5. RESULTS AND DISCUSSION

This section shows the results obtained from the study of the cases explained before. The section has been structured in three parts in such a way that, first, the feasible set of combinations for each case are detailed, then, the most representative results are collected in Table 4 and hence a comparison among them can be performed, and finally, a detailed analysis of the obtained results for the Case 3 is presented.

- Case 1: Infinite availability of grey water

Figure 9 depicts the possible sizes combinations for the optimal α that meet the discomfort standards described in the methodology section. Figure 9a refers to the operating hours, Figure 9b refers to the COP of the system and Figure 9c refers to the associated CO2 emissions.

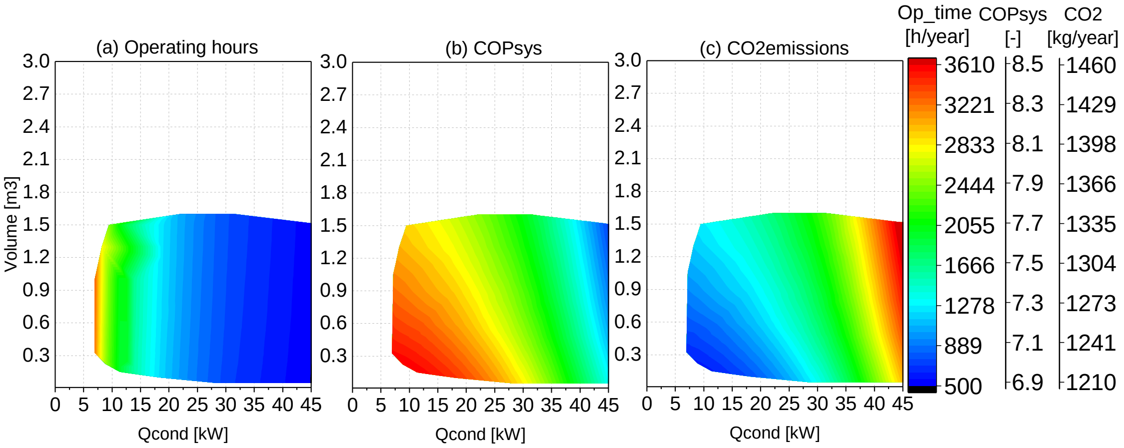

Figure 9: Annual operating hours, COP of the system and CO2 emissions associated to an infinite availability of grey water heat source and the optimal alpha.

According to Figure 9, low-temperature heat source has a great energy recovery potential in DHW production applications. There is a wide range of HP-ST$_{DHW}$ combinations that result in similar CO2 emissions (around 1230kg/year) and these combinations are capable of operating under COPs values up to 8.5 with operating hours around 2200 hours (6h/day). According to Figures 10 b) and 10 c), the best combinations are found for small heat pumps and small DHW storage tanks. The figure also shows that as the size of the heat pump is reduced, the size of the storage tank increases and there is a minimum size for the tank and for the heat pump which allows to satisfy the DHW demand. 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$_{DHW}$=250liter.

To be able to numerically compare the results obtained for each case, that case has been taken as a base case out of all the possible best combinations. These results are presented in Table 4.

- **Case 2: Finite availability of grey water**

This case corresponds to the assumption that grey water is generated uniformly during the year and that the total amount generated is the same as that obtained using the grey water profiles defined in section 2. The water temperature conditions are the same as Case 1 (33ºC).

Figure 10 shows the possible ST-HP combinations for the optimal α that meet the discomfort standards described in the methodology section when the grey water is limited to the considered availability. Figure 10a refers to the operating hours, Figure 10b refers to the COP of the system and Figure 10c refers to the associated CO2 emissions.

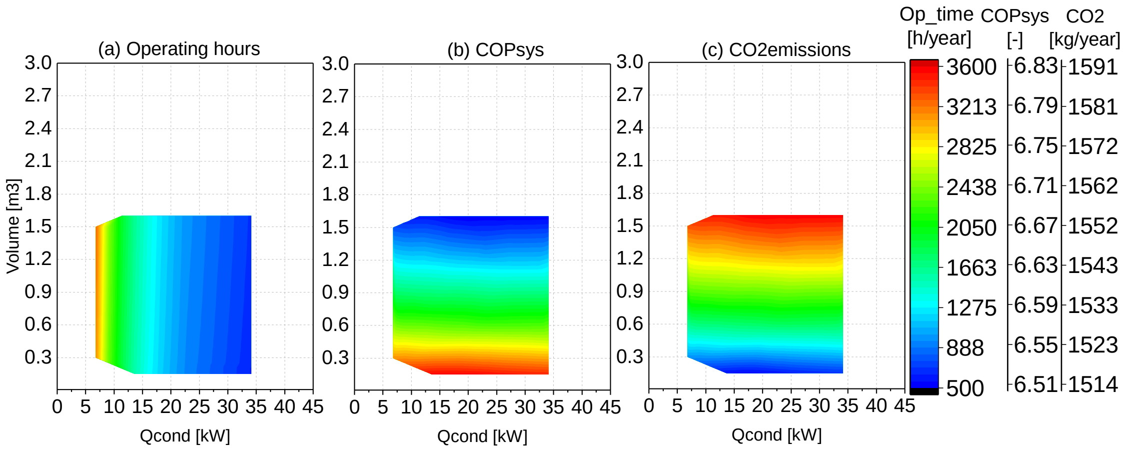

Figure 10: Annual operating hours, COP of the system and CO2 emissions associated to a finite available grey water heat source and the optimal alpha.

In this case, the limitation of m_{wgr}, 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 is the most influential variable on the performance and optimum system configurations are found in a narrower band of ST_{DHW} volumes.

According to Figure 9 and Figure 10, from the comparison of the optimal solutions in both systems, the limitation of the grey water available 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).

- **Case 3: Finite and variable availability of grey water**

In order to design these systems, similar results to the ones shown Figure 10 were obtained from the parametric studies performed in Case 3a and 3b. With the ST_{DHW} and the scale parameter obtained for these cases, the variable availability demand system was simulated (cases 3c and 3d), adapting in this case the values of α in order to respond to the variable availability of grey water. Table 4 collects the most important results of each case.

Table 4: STgw-HP-STdhw optimal combinations for infinite availability of the heat source, finite availability but constant, and finite and variable availability. Grey cases correspond to constant water temperature design conditions and has been used for sizing case 3c and 3d but they do not represent any physical result analysed in this work.

		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 cond. $Scale_{min}$	0.15	6.81	500	1250	0.9	6.67	3175	1540.3
3d	Real cond. ST_{dhwmin}	0.25	11.38	350	875	0.5	6.72	1890	1529.1

According to the results for the cases 3c and 3d shown in Table 4, with the proper system design, a heat pump with a nominal capacity between 6.81-11.38 and a DHW storage tank between 500 to 350 could be enough to supply the DHW of a set of 20 dwellings using the grey water produced by them.

Performing a deeper analysis of the results and selecting for simplicity the cases with the minimum DHW storage tank sizes (same comments can be done for the cases with the minimum heat pump size). Comparing the Case 1 (infinite grey water availability) with the Case 2b (finite but constant grey water availability), it can be seen that the heat pump size increases in 30%, this increase is even higher, 40%, when Case 1 is compared with Case 3d (finite and not constant availability). Regarding the DHW storage tank, it does not change from the Case 1 to the Case 2b but it increases in 40% when the variability in the heat source is introduced (Case 3d). Concerning the COPsys, the limitation in the heat source availability reduces significantly the COPsys, however, it is noticeable that once the design is dynamically adapted to the variable conditions (cases 3c-3d)., the difference in COPsys between Case 2 and Case 3 is lower than 2%. This fact reveals that with a proper system design, the variability in the availability of m_{gr} does not have an important impact on the final system efficiency.

In order to properly understand the dynamics of a system based on grey water energy recovery, later, the results of case Case 3d are going to be analyzed more in deep.

Figure 11 shows the levels and temperatures of the water stored in both tanks for a one-minute time scale and annual simulation. Figure 11a represents in grey the evolution of the level of the grey water with time within the ST_{gw} and in red the evolution of the level of the hot water with time within the ST_{DHW}. Figure 11b represents in grey the evolution of the stored grey water temperature with time within the ST_{gw} and in blue the stored grey water temperature evolution of the level of the hot water with time within the ST_{DHW}.

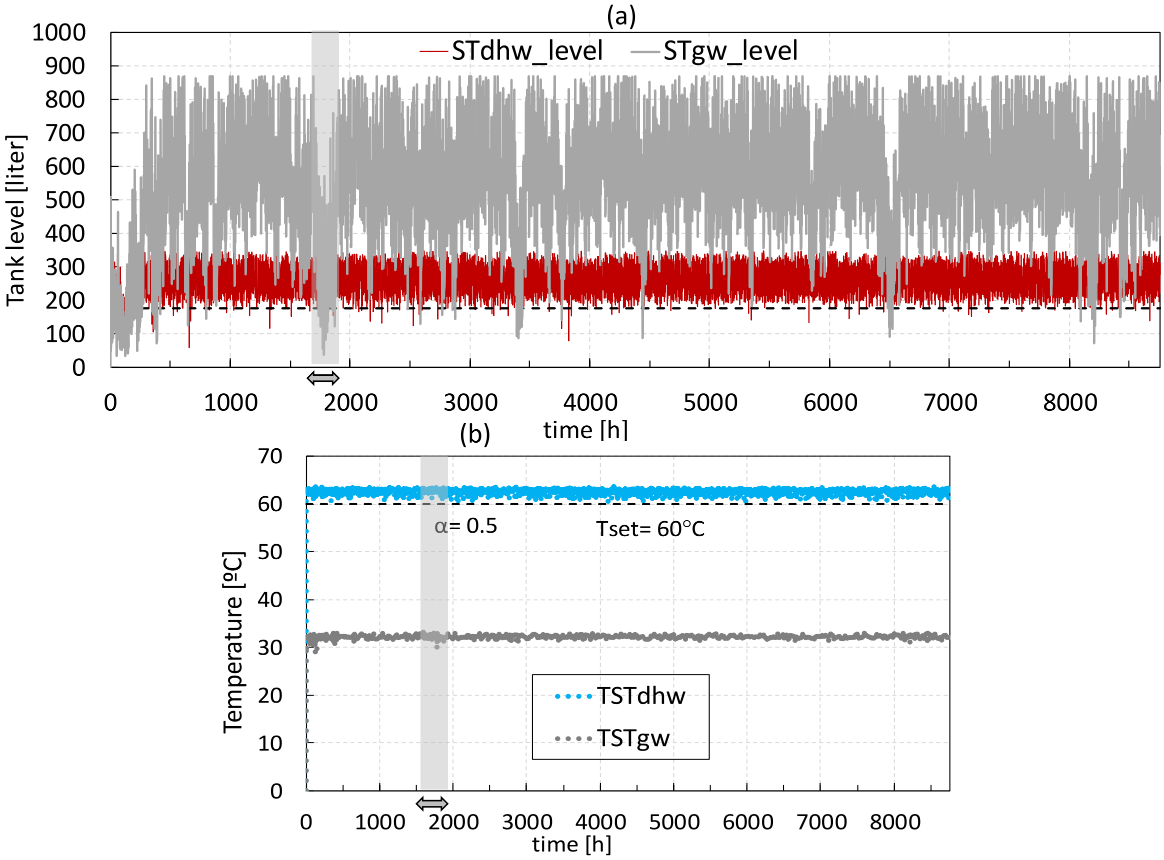

Figure 11: STgw, ST_{DHW}, T_{STgw}, T_{STDHW} for one-minute time scale annual simulations and the optimal solution (case 3d).

It can be seen in Figure 11, that the temperature within the ST_{DHW} never falls below 60ºC (design requirement) and the temperature of ST_{gw} never falls below 25ºC (non-stationary design requirement).

In order to appreciate in more detail, the behavior of both ST, Figure 12 shows, for a period of 48h, the levels, temperatures and inlets/outlets mass flow rates. Figure 12aa represents the stored water mass flow rate balance in the ST_{DHW}. The red color indicates the inlet water temperature (from the condenser), the blue color represents the required water flow rate from the demand and the dot-filled black pattern represents the water mass flow rate leaving the ST_{DHW}. Figure 12b represents the temperature and level evolution of the stored water mass in the ST_{gw}. The grey color corresponds to the level and green dotes are used for the hourly-average temperature. Figure 12c represents the stored water mass flow rate balance in the ST_{gw}. The orange color indicates the inlet water temperature (from the drain), line-filled black pattern represents the required water flow rate from the heat pump operation and the grey color represents the water mass flow rate leaving the ST_{DHW}.

From Figure 12a, it can be seen that the demand is always satisfied (blue bar always is paired with dotted bar). Figure 12b shows that also there is always enough grey water to satisfy the heat pump demand. According to Figure 12c variations up to 5ºC are registered in the ST_{gw} and the grey water tank is never empty.

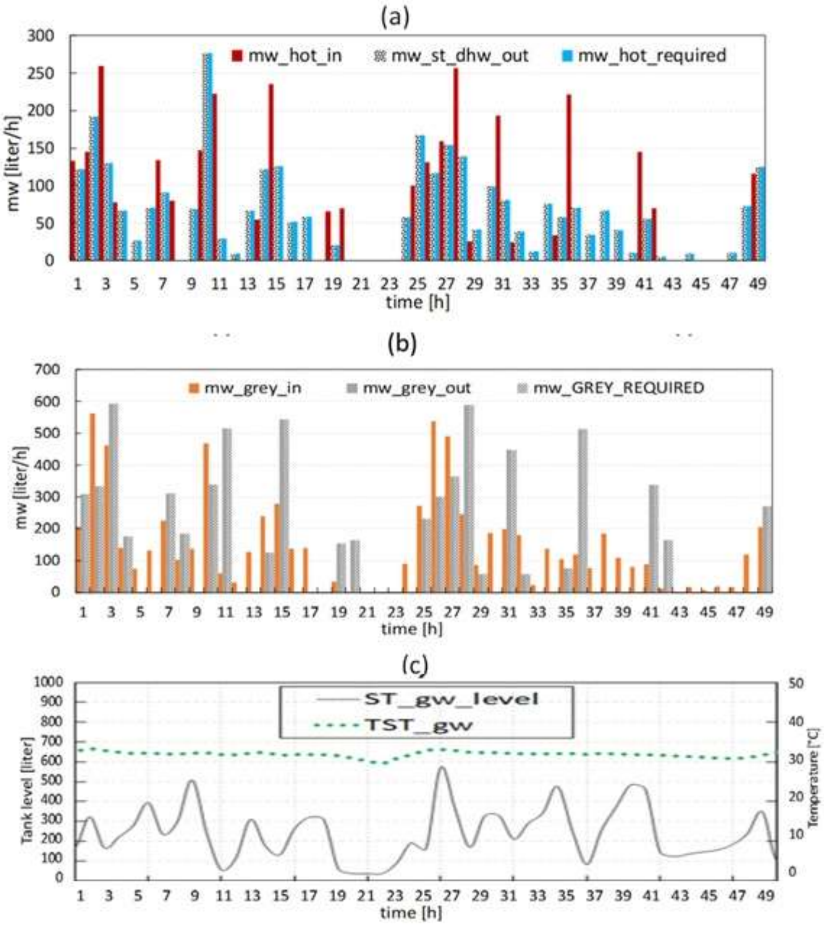

Figure 12: 48h STs behaviour in terms of mass flow rates, temperatures and level of the water stored.

Figure 13 represents monthly energy and COP values. Figure 13a contains the energy information. Columns in red represent the monthly heating energy supplied by the HP, and columns in the line-filled black pattern represent the heating energy supplied by the

HE. The grey line represents the energy demanded by the user, and dotted blue lines represent the final energy supplied to the user. Figure 13b shows the monthly average efficiency. Blue dotes are used for the system (COP_{sys}) and red triangles are for the heat pump (COP_{hp}).

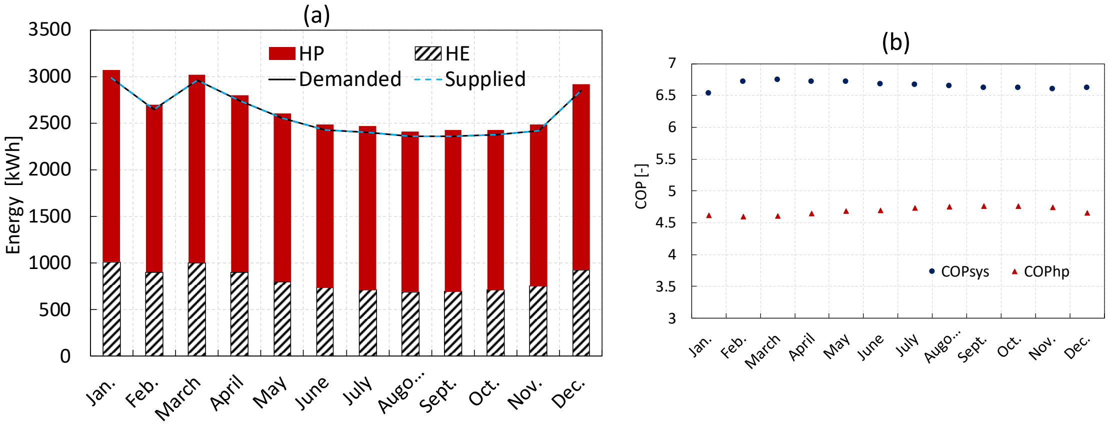

Figure 13: Monthly energy consumption, demand and supply in addition to average heat pump and system performances.

As it can be seen in Figure 13a, a significant proportion of the energy used for heating is obtained from the HE. The energy obtained from the HE is greater during cold months (results in line to the potentiality seen in Figure 6). The energy demanded and supplied are superposed indicating that the demand is satisfied by the system in terms of energy. The difference between the energy employed to satisfy the demand and the energy supplied to the user indicate the system losses. The efficiency of the system remains above 6.5 throughout the year with highest values in cold months. This is a consequence of the fact that the temperature of the grey water does not depend on the season and there is more recovery potential when the tap water is colder. It is also noticeable that in Figure 13b,the optimum in COPsys does not match with the COPhp showing the relevance in the system design of adopting a holistic approach to the system.

Figure 14 contains the main characteristics of the grey water heat source. Figure 14a represents the monthly grey water energy extracted by the HP (grey column) and by the HE (line-filled column), The grey energy available is shown in light brown. Figure 14b also shows the percentage of energy extracted from the total available. Figure 14b shows the temperature of the grey water at the outlet of the evaporator (grey water temperature to the sewage) throughout the year.

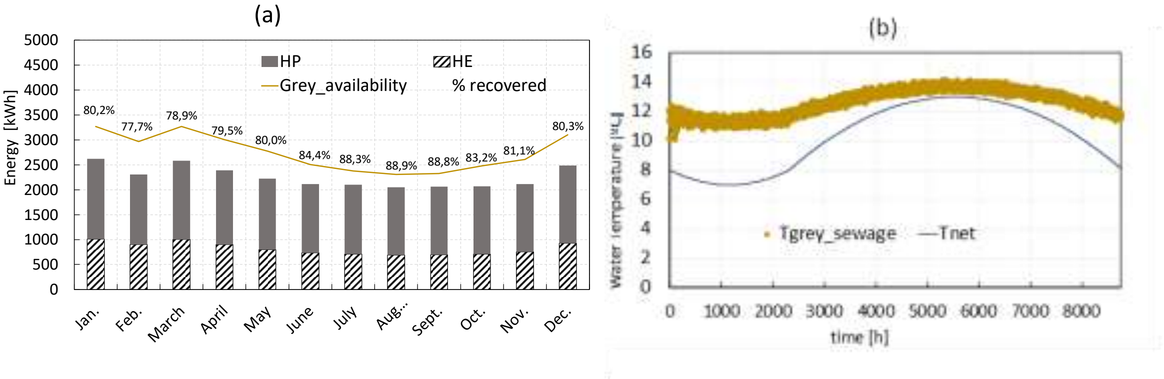

Figure 14: Monthly grey energy recovered and available and final annual grey water outlet temperature (to the sewage).

As it can be seen in Figure 14, a significant heat extraction is done by the HE with slightly seasonal fluctuations. From the energy available to extract (considering the minimum water temperature of the sewage as the water temperature from the net), an average extraction of 83% has been enough for the DHW supply. Figure 14b 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, and therefore the system is able to satisfy the DHW demand only with recovered energy from the dwellings. In addition, Figure 14b also shows that the energy recovery system is more effective during the colder months.

These results highlight the great potential of grey water heat recovery as a heat source for DHW production based on a HE and a HP.

6. 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. In order to do that, a system configuration has been defined to maximize the efficiency of the recovery potential. This configuration includes not only the system topology which includes a heat exchanger plus a heat pump but also the right design of the heat pump and the accumulation strategy in the water storage tanks.

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 and the influence of contour conditions in the energy consumption. Finally, a system in order to satisfy the DHW demand of 20 dwellings under a moderated climate using their grey water production as a heat source has been analyzed in detail. The obtained results for this case have shown that with the proper sizing and control of the system a relatively small heat pump (6-12kW) with a variable volume DHW tank of 500 l is able to satisfy the required demand.

In addition, the following results has been also obtained:

- A decrease of 20% in the efficiency is produced when having the heat source at the same mean temperature, the availability of water heat source is limited to the amount of grey water produced by the dwellings.
- Having a variable availability of grey water increases significantly the size of the components (for instance, double ST_{DHW} capacities for the minimum HPsize).
- The variable grey water availability does not penalize significantly the system efficiency. The decrease on the performance is only 2% compared to the case with a constant availability of grey water (case 2).
- The grey water temperature at the outlet of the evaporator is always higher than the net water temperature. Hence, the system is able to satisfy the DHW demand only with energy recovered from the grey water.

- Considering that energy can be extracted from the water strictly under recovery conditions (until it reaches the value of the net water temperature) only with the extraction of 83% of the total energy has been enough in order to satisfy the DHW demand. To obtain this result, all the grey water produced by the dwellings must be used and not only the grey water coming from the DHW.
- The advantage of this type of system is higher when the ambient temperatures are lower. Therefore, these results could be more significant when this kind of system is applied to cold climates.

Finally, it is known that heat pumps are very good systems for energy recovery applications. Nevertheless, the efficiency of them could increase significantly with the system configuration proposed in this work for the case of DHW production based on the grey water produced in dwellings. In fact, the presented approach can be extended to other energy recovery applications where a heat transformation is required as the principles of this work are only based on: having a source of waste heat and having the necessity of increasing the temperature of tap water significantly.

APPENDIX

In Section 3 and based on the definition of the amount of energy that can be extracted from a heat source using a heat pump, it has been stated that once we have defined the inlet and outlet temperatures of the heat source and the heat sink a criteria to define the optimum mass flow for a given HP in order to satisfy a given demand can be supplied.

This appendix has the target of explaining the way in which that criteria is obtained.

From Equation (14), C_{0r} is always lower than C_{0i} (equal only in the ideal case). For a given demand, m_{w_hot} is constant, and in a real system three situations can be found related to m_{wgr} when the inlet and outlet temperatures of the heat sink and heat source are fixed:

a) **$C_0 > C_{0i} > C_{0r}$:** In this case, there is enough grey water mass flow rate available to recover the required energy to satisfy the demand. m_{wgr} used would be $m_{w\_grey} = C_{0r} m_{w\_hot}$. The rest of the grey water would not be required by the system to satisfy the demand. Regarding the energy consumption, the additional heat W_{cah} that the user must supply to the system directly (COP=1), is in this case $W_{cah} = W_{ci} = Q_{heating} - Q'_{recovered}$. Even though there is an excess of grey water available it cannot be used to satisfy part of the demand.

b) **$C_{0i} > C_{0r} > C_0$:** In this case there is not enough grey water available to recover enough energy to satisfy the heating demand. The amount of water that can be heated by heat recovery is given by $m_{w\_hot} = \frac{m_{w\_grey}}{C_{0r}}$ and the rest of the water heating demand must be supplied by other methods. In this case the additional heat that the user has to supply to the system directly is $W_{cah} = W_{ci} + W_{Res}$, where W_{Res} is a heating capacity that can be supplied by an electrical heater or other alternatives and its value is given by:

$$W_{Res} = (m_{w_{hot}} - \frac{m_{w_{grey}}}{C_{0r}})(T_{hot} - T_{net}) \tag{A.1}$$

It is important to point out here that in this case, while the COP_{HP} maintains the condition **$C_{0r} > C_0$,** it will not have an influence in the energy consumption of the system. A change in the COP of the heat pump only changes the ratio between W_{ci} and W_{Res} but not the total consumption, at least while the condition **$C_{0r} > C_0$** is preserved, that is:

$$COP_{HP} > \frac{1}{1 - \frac{C_0}{C_{0i}}\left(1 - \frac{1}{COP_{Lorenz}}\right)} \tag{A.2}$$

c) **$C_{0i} > C_0 > C_{0r}$:** In this case there is not enough grey water availability to ideally recover enough energy to satisfy the heating demand but there is enough grey water availability to satisfy the demand with the used heat pump. The situation would be very similar to the first case and there would be a fraction of the grey water that cannot be used. Nevertheless, in this situation the room for improvement in the COP of the heat pump is limited by the condition $\mathbf{C_0 > C_{0r}}$, which means that the user can improve the COP of the heat pump (reducing the total consumption of the system) until it reaches a limit value:

$$COP_{HP} = \frac{1}{1-\frac{C_0}{C_{0i}}\left(1-\frac{1}{COP_{Lorenz}}\right)} \tag{A.3}$$

From there, any improvement in the COP of the heat pump will not have any effect on the energy consumption of the system.

It should be pointed out that this analysis was applied in this article using a temperature difference in the evaporator of 4.5 K a value for C_{or} of 8.9 and a value for C_{oi} of 10.4, and for all the cases the situation of this work was the one corresponding with the situation c).

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