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Title: Optimal sizing of a heat pump booster for sanitary hot water production to maximize benefit for the substitution of gas boilers

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Keywords: heat pumps; sanitary hot water; waste water; low grade heat recovery; optimal size

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Abstract: Heat recovery from water sources such as sewage water or condensation loops at low temperatures (usually between 10-30°C) is becoming very valuable. Heat pumps are a potential technology able to overcome the high water temperature lift of the Sanitary Hot Water (SHW) application (usually from 10°C -60°C with COPs up to 6). This paper presents a model to find the optimal size of a system (heat pump and recovery heat exchanger) based on water sources to produce SHW compared to the conventional production with a gas boiler in order to maximize the benefit. The model includes a thermal and economic analysis for a base case and analyze the influence of a wide set of parameters which could have a significant influence. Even the uncertainties involved, results point out considerable benefits from this substitution based on the capacity of the system. Thus, demonstrating the importance of the optimal size analysis before an investment is done.

ENERGY
Editorial board

Dear Sir/Madam,

I am writing to enquire about the publication of the manuscript entitled

“**OPTIMAL SIZING OF A HEAT PUMP BOOSTER FOR SANITARY HOT WATER PRODUCTION TO MAXIMIZE BENEFIT FOR THE SUBSTITUTION OF GAS BOILERS**” in your high-impact journal *Energy*. The authors, estefania hervas, miquel pitarch, emilio navarro and jose miguel corberan, have worked on the study of the optimal size of a heat pump and a recovery heat exchanger in order to maximize the annual benefit compared to a conventional gas boiler for the production of sanitary hot water.

The work hereby presented is completely original, has been done only by these authors and has not been send to any other journal or publication. All authors have read and agreed to its content. In addition, authors to declare any competing financial or other interest in relation to their work.

I look forward to hearing from you.

Yours faithfully

Estefania Hervas

Institute for Energy Engineering
Technical University of Valencia

*Point-to-Point Response to Reviewers

Reviewer #1: The paper is interesting and deals with a novel application (HP booster for HSW production recovering heat from sewage water).
The method is correct and the results consistent.
The English has to be double-checked for some minor typos along the paper

Thank you very much for your observation, some English corrections have been done.

Some suggestions are given as follows:

1) The nominal capacity is fixed to a very specific value: 42.631 kW. It could be useful to explain if it is the capacity of a real case tested experimentally and used to calibrate the model or not.

Thank you for your observation. The size is the existing prototype size with which the experimental tests and the model validation have been done. A new line clarifying this point has been added to the manuscript.

2) The nominal mass flow rate of the sewage water is 7000 kg/h. Why? have you fixed the DT at the water side for a specific power? this is an important aspect since it affects all the simulation (may be someone was expecting a sensitivity analysis vs the mass flow rate of the sewage water, so please explain this choice)

The evaporator water mass flow rate was chosen to follow the procedure stated in the European Standard EN 1485.

Nevertheless, different water mass flow rates could be applied and the same study could be done. However, the aim of the manuscript is to show a methodology in order to find an optimal size of a recovery heat exchange and a heat pump and the study is made for a set of assumptions that are just an example.

The available sewage water mass flow as well as its temperature is a critical variable that influences the simulations results. In fact, different water mass flow rates would lead to a different final benefits. However, the best result and the maximum ratio would still be the same.

A new approach has been adopted in the paper in order to clarify this and generalize a bit more the work. Please find below three different analysis for three different water mass flow rate at the evaporator side. The base case is represented in Figure 1b (that is, 7000 kg/h and 8760h of availability) while Figure 1a takes into account the same assumptions as the base case changing the water mass flow to 3500kg/h and Figure 1c to 14000 kg/h.

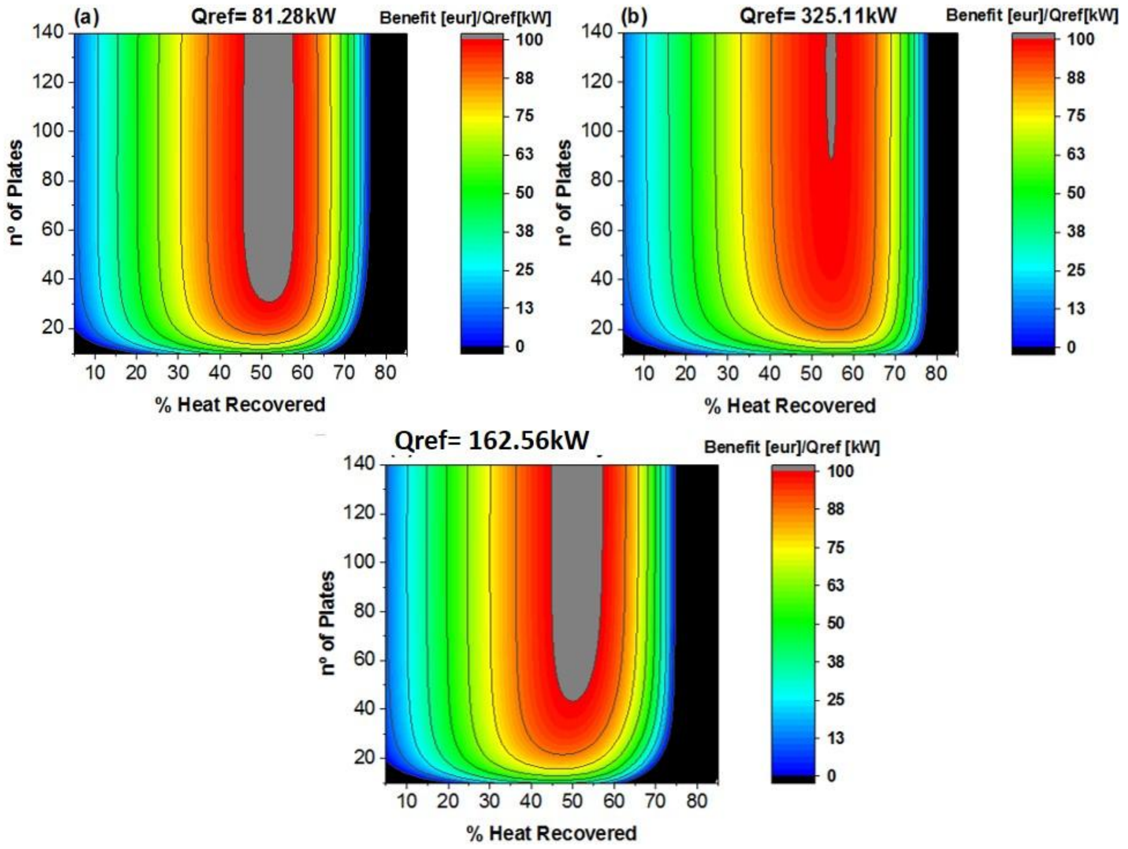


Figure 1: Ratio Benefit variation function of the evaporator outlet water temperature [Tout_evap] and the number of plates for the base case assumptions and different water mass flow rates. (a) 3500 kg/h (b)7000kg/h (c)14000kg/h

According to Figure 1, the benefit would be lower as lower sewage mass flow rate is available but not the ratio which has similar values for the three cases as well as the most profitable solution.

With regards to the heat exchanger, Figure 2 of this document represents the benefit for the 51% of heat recovered and the number of plates in the base case.

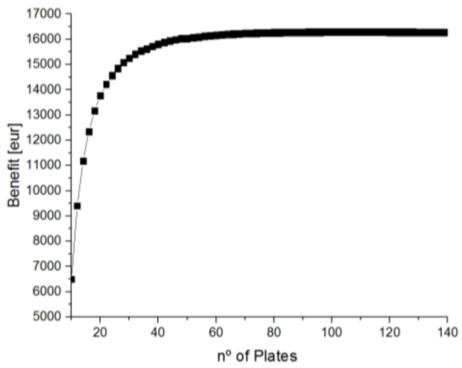


Figure 2. Variation of the Benefit with the number of plates of the heat exchanger for the maximum ratio and the base case.

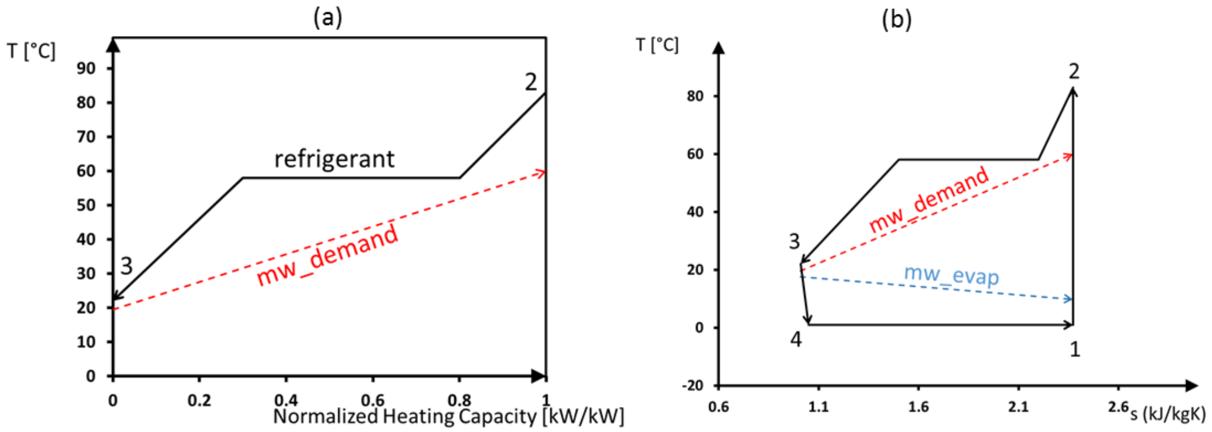
This figure follows a pattern similar to Figure 3b of the manuscript and the same with the respective benefit for the other sewage mass flow rates. Around 80 plates the shape becomes very flat being this number a good estimation for the optimal design of the HE.

3) More details about the fact that the HP is a special version with an optimal subcooling are required since this is not a usual solution and the reader could jump this part and it could

come to not correct conclusions. A temperature profile at the condenser + T,s diagram is suggested in nominal conditions

Thank you for your objection, the setup of the heat pump prototype used to validate the model allows the use of a high subcooling. The system produces the maximum possible subcooling for the system and the respective conditions. In reference [22]. In fact, this heat pump has been developed under the 7 framework program of the European Union by the project Next Generation of Heat Pump Technologies (NEXTGHP) grant agreement 307169 and for the equations considered in the model, the maximum subcooling has been applied. This was the first step for further research regarding to the optimal subcooling for a given conditions that are being investigated at the present.

Figure 3a shows the temperature profile at the condenser and Figure 3b the T,s diagram considering the maximum subcooling for nominal conditions nominal conditions (size=1, sewage temperature = 20ºC, considering the recovery heat exchanger for the optimal size which implies a water evaporator inlet temperature of 18.72ºC, the condenser water inlet temperature equals to 19.81ºC and the condenser outlet water temperature equals to 60ºC). Reference 22 includes more details about the heat pump and its characteristic that the authors do not include in this paper due to space constraints.



4) In Eq 19) the symbols like DPpump_cond etc are used to refer to the power but they can be confused with the DP at Eq 16 and 17; it is strongly suggested to use different and more consistent symbols

Thanks for the comment, the symbols have been changed and we hope now both equations can be better understood.

5) In Eq 20 DPpump_cond is not negligible??

Thanks for your observation. In fact, you are right and this term could be negligible (for nominal conditions it accounts for 0.3% of increase in the heating capacity). Nevertheless, it has been taken into account in order to follow the European Standard 14511-3 which considers this term for the calculation of the COP and the heating capacity.

6) To decide the price of the electricity the assumption that the recovery system is working 8760 h per annum was done (see page 19 after table 1); then a sensitivity analysis was made changing the amount of hours per annum. In the new cases how did you establish the costs? they are affect by the moment of the day when the energy is required. Please specify

Thank you very much for this comment. . In order to study different running periods within the day/different prices, a demand profile would need to be considered and this is out of the scope of this work.

In this case, the reference has been chosen to be 8760h/year (24h/day). Nevertheless, the electricity price used is based on the weighted average electric price of 3 periods (according to the numbers state in Table 1 of the manuscript). The sensitivity analysis on the number of working hours aims more to study how important are the running hours in the final solution rather than when they occur. The same price has been extrapolated to the other working periods considered (4380h,2920h and 1460h).

7) Following the analysis in FIg 3 is not clear if the subcooling is adapted each time you change the number of plates

Thank you for this point. Yes, in fact, the subcooling is always the maximum possible at every condition for the minimum heat pump size. This means that as the number of plates change, so the inlet water temperature at the evaporator and condenser do. Therefore, the heating capacity changes and the maximum possible subcooling for the new conditions changes as well. A new sentence has been added in the manuscript to clarify this.

8) Data about specific costs seems to be missing before the economic analysis

Thanks for this remark. In fact, there are more costs that could be included in the manuscript. However, due to space constraints and the number of variables involved in the problem we thought only in adding what the authors have considered the most important costs.

9) After Fig 8 the comment about the influence of the ratio of the electricity/natural gas costs is of great influence, it could be interesting to apply this analysis to some real cases in Europe were this ratio is strongly variable (Consider Serbia or Great Britain vs Italy or Germany.. there are strong variations for the costs. You can find the data here: http://ec.europa.eu/eurostat/statistics-explained/index.php/Energy_price_statistics)

An example with actual, real costs would help to fix ideas.

Thanks for this suggestion and the given link. The consideration of real cases as well as the comparison between those so different countries could be very interesting. However, it is out of the scope of this manuscript. The base case prices are for example as the ones in Ireland for the electric prices and in Luxemburg gas prices which are a ratio electricity price/gas price = 3.25 considering for the price all the taxes.

If we consider Serbia vs Italy, for example, the first case accounts for an electric/gas price ratio equals to 1.709 which means that in Serbia the electricity is comparatively cheaper with regards to the gas price as in Spain. Therefore, the substitution of the gas boiler by a heat pump would lead to even higher benefits and/or bigger heat pump optimal sizes. The case of Italy has an electric/gas price ratio equals to 1.97 which lead to a similar conclusion as for the Serbia case. Moreover, the benefit in quantity would differ from one to another country based on the prices.

Finally, yes, it would have been a really interesting analysis for the manuscript but due to the limited extension, we consider that is out of the scope of this work.

10) Check if you have cited the most relevant and actual works about natural refrigerants with HP are cited

New references on the natural refrigerants used in heat pump for DHW have been added.

Reviewer #2: The paper is interesting and well organized.

Some changes are needed:

1) IN the result the case of efficiency equal to zero for the heat recovery HX is not discussed. This case would be expected to be more efficient for a normal HP since the benefit to the evaporator is larger than the penalty to the condenser (in terms of entropy generation). In this specific case probably the fact that the heat pump uses an optimized subcooling can change the results. But this is an important point to be clarified.

Thank you very much for this comment. If we have understood correctly, the case where the efficiency of the heat exchanger is zero is the first case analyzed within the results and discussion section where the comparison between the performance and the benefit between the heat pump and the system heat pump plus heat exchanger is done.

As you said, the heat pump would be expected to be more efficient without the heat exchanger and it is correct for both cases, a normal heat pump and this heat pump which operates with maximum subcooling. However, the system considered as the heat pump + a heat exchanger (and it is valid for a normal heat pump and a heat pump with subcooling) has a higher performance than the heat pump alone. This means than with the HX, the COP of the heat pump is lower than operating the heat pump alone. Nevertheless, the global performance of the system (HX and HP) brings a higher benefit than the heat pump itself.

A new paragraph has been included to the manuscript in order to clarify this.

As it is stated in Table 3 of the manuscript, the case where only the heat pump is considered has a COP of 5.66 while the system (heat pump + heat exchanger) has a COP of 5.142 (the same is expected to happen if none subcooling is used). However, the COP used in the economic analysis for the calculation of the Benefit is the COP_total which includes the auxiliaries and the HX heat exchanged. In this case, the COP_total of the heat pump alone is 5.649 while the COP_total of the system (HX and heat pump) is 6.356 and that is the reason why the system is leads to higher benefits than the heat pump itself.

2) The part of Eqs 10 and 11 it is not clear. Simplify and explain the symbols

Thank you very much for this observation. In fact, there was a mistake on the equations. They have been corrected and the symbols further explained. However, the approach of the paper has also been changed in order to generalize a bit more the work. Therefore, those equations have been removed.

3) Eqs 16 and 17 probably are wrong (a symbol missing in the second term at the right hand side)

Thank you very much for the observation. In fact, some symbols were missing in the final version. The equations have been corrected.

4) Probably Eq 25 expresses a simple payback time since there is not actualization of costs? if yes it is important to specify this

Thanks for this comment. The payback time is just a simple calculation based on the annual savings and costs which include the cost actualization but this indicator does not include it according to the methodology followed in the reference [24] of the manuscript.

A new sentence clarifying this has been added to the manuscript.

“Notice that this is a calculation that does not include the actualization of the values but is a ration which components have been actualized previously following the methodology stated in [28]”

5) Fig 5 b) more comments about the fact that the solution with maximum COP is not the one with the maximum benefit are needed (The influence of the size of the HEAT PUMP on the total energy consumptions is not clear if the part related to the integration by the gas boiler is not included)

Thank you very much for this point. A more detailed discussion about the optimal solution which is not the highest COP has been included in this section to the manuscript. The size of the heat pump is directly the heating capacity of the heat pump. On the one hand, this heating capacity is related with the heating capacity by the relation with the COP for that conditions which is translated into an electric consumption. On the other hand, that heating capacity would have been produced by the gas boiler which leads to a gas consumption. The annual saving is the difference between the production by means of a heat pump and a gas boiler while the benefit is difference between the annual saving obtained and the annual investment cost incurred. New comments on this line have been added within the economic part, in the 2.2.2. Economic problem section.

Reviewer #3: The subject addressed by this paper is of growing importance, but the investigation which has been carried on has a limited interest, due to the non-generality of the work.
The main evidence of this is in the "main conclusions" of your work. You state: "For the base case, the maximum benefit is 16840€/annually, the optimal size of the heat pump is 104kW and the number of plates equals to 110 for the heat exchanger. The system Coefficient of Performance (COP_total) is 5.35 and the SHW production equals to 1769kgh-1 constantly produced for the 8760h of the year which is translated into a cost of 0.042c€/liter of SHW apart from the benefit obtained."

Personally, I don't deem these conclusions of any usefulness except to the authors.
Try to generalize your work a bit more.

Thanks you very much for your comment. Following your recommendations, we have tried to give a conclusion following a more general approach and we have restructured the work in terms of new parameters in order to generalize the work.

The conclusions and most of the document have been updated according to this.

At least, give a description of the main user features (how many people?). You should also consider the schedule adopted by them and evaluate the system under dynamic conditions. The considered example does not include a demand profile.Using continuously SHW 8 hours/day is not the same as using it one hour every third hour.

Thank you for this suggestion. The use of the SHW as well as the availability of the heat to recover is crucial when trying to make an investment of this type. In this work a demand profile and a sewage availability profile have not been considered. Instead, the assumption that there will always be available heat to recover and there will always be an instant demand to consume the SHW produced have been assumed. This is because the aim of the work was focused on a big consumer/producer and the main expected conclusion was to see whether the substation of part of the production with a condenser gas boiler by a heat pump was or not interesting. This study is the first step of a thesis within the project “Low temperature waste heat recovery with heat pumps for hot water production” and the introduction of a demand profile and a storage tank based on that demand will be done in further steps. However, at this moment the aim of the work was to define a methodology that leads to maximum benefits for sanitary how water productions and to see which are the main influence variables in the problem.

The use of a demand profile as well as a storage tank will introduce dynamic conditions to the problem that are specific to an application which is out of the scope of this work.

The equations adopted for simulating the HP COP are empirical equations apparently valid for steady-state conditions. How were they found?

The equations used for the HP COP as well as for the heating capacity were found experimentally for steady state conditions thanks to a heat pump existing prototype which characteristics are commented in section 2.1. Description of the system and further detailed in the reference [22]

And actually your system does not include any storage tank, which seems to me quite unusual for a large SHW system.

Thank you very much for this comment. In fact, this type of systems used to operate with a storage tank sized for a specific application based on the demand profile. As commented previously, this work aims to define a robust methodology as well as to study the influence of different variables in the final benefit for an investment on a heat pump for SHW production. This is only the first step and a specific application needs to be considered in order to further design the final system.

The hypothesis that "the wastewater mass flow rate is constant and available during all the hours of the year" does not seem credible.

Thanks for this consideration. As commented before, the first approach was to considered a very big sector where the SHW demand is more or less constant as it is the available heat to recover. This could be for example the heat coming from condensing loops from a freezer.

Different available mass flows and profiles could of course be considered and them would impact in the final maximum benefit but not in the optimal solution. The authors hope that the new approach followed in the paper can be a bit more general and answer this question.

How would different usage schedules affect your results?

Finally, different usage schedules would affect the results in many ways, it would depend on the existence or not of a storage tank, the size of it, the price of the electricity based on the period and so on. In this work a much bigger demand than the production has been assumed as an example in order to fix one of the many variables that take place in this type of problems.

This last question is directly linked to the two previous questions. A study about these points would be of great interest, but it is out of the scope of this work. In fact, the authors consider that probably this type of study could constitute an article by its own.

HIGHLIGHTS

- To substitute a gas boiler by a heat pump for SHW is thermo-economically profitable.
- Optimal sizing of a heat pump and a recovery heat exchanger to maximize benefit.
- The introduction of a recovery heat exchanger is always positive
- The maximum benefit does not correspond to the highest heat pump COP.
- The most influent external variable on the benefit is the number of operating hours.

TITLE:

Optimal sizing of a heat pump booster for sanitary hot water production to maximize benefit for the substitution of gas boilers

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ABSTRACT

Heat recovery from water sources such as sewage water or condensation loops at low temperatures (usually between 10-30°C) is becoming very valuable. Heat pumps are a potential technology able to overcome the high water temperature lift of the Sanitary Hot Water (SHW) application (usually from 10°C -60°C with COPs up to 6). This paper presents a model to find the optimal size of a system (heat pump and recovery heat exchanger) based on water sources to produce SHW compared to the conventional production with a gas boiler in order to maximize the benefit. The model includes a thermal and economic analysis for a base case and analyzes the influence of a wide set of parameters which could have a significant influence. Even the uncertainties involved, results point out considerable benefits from this substitution based on the capacity of the system. Thus, demonstrating the importance of the optimal size analysis before an investment is done.

Keywords: heat pumps, sanitary hot water, waste water, low grade heat recovery, optimal size

NOMENCLATURE

m_{demand}: SHW mass flow rate capacity, tap water flow [kg s^{-1}]

m_w: wastewater mass flow rate [kg s^{-1}]

cp_w: specific water heat [J kgK^{-1}]

T_{grey}: wastewater temperature [ºC]

T_{tap}: fresh/tap water temperature [ºC]

T_{in_evap}: evaporator water inlet temperature [ºC]

T_{out_evap}: evaporator water outlet temperature [ºC]

T_{in_cond}: condenser water inlet temperature [ºC]

T_{out_cond}: condenser water outlet temperature [ºC]

T_{evap}: fluid evaporating temperature [ºC]

W_c :compressor consumption [kW]

Q_{ref} : available heat to recover assuming a lowest water temperature of 0°C [kW]

Q_{evap}: cooling capacity [kW]

Q_{heat}: heat exchanged in the heat exchanger [kW]

Q_f : fuel heating capacity [kW]

ε: heat exchanger effectiveness

DP_{evap} :water drop pressure through the evaporator [mbar]

DP_{cond} : water drop pressure through the condenser [mbar]

DP_{demand} : fresh water drop pressure through the HE [mbar]

DP_{water} : wasted water drop pressure through the HE [mbar]

$Power\_pump$: consumption of the water pump [kW]

η_{pump}: pump efficiency [-]

ρ_w: water density [kg (m3)$^{-1}$]

η_{cald}: boiler efficiency [-]

Economic

i: bank interest rate [%]

n: annual payments [years]

r : annuity [-]

$C_{y\_total\_m}$: Annual equivalent investment cost of *m* [€ year^{-1}]

C_{a_m}: Annual cost of the element *m* [€ year^{-1}]

C_{y_m}: Yearly costs of *m* related to taxes [€ year^{-1}]

C_{i_m}: Initial investment cost of *m* function of its size [€]

C_{s_m}: Residual value of *m* after the *n* years [€]

$C_{y\_op\_m}$: Annual operating cost of *m* [€ year^{-1}]

C_{elec_energ} : electricity price (energy term) [€ kWh^{-1}]

C_{elec_pow}: electricity price (power term) [€ kW^{-1}]

C_{maint_k}: annual maintenance cost of *m* [€ year^{-1}]

$C_{\_fix\_gas}$: fix part of the gas price [€ year^{-1}]

$C_{\_fuel}$: gas price [€ kWh^{-1}]

t: operating hours of the installation [h]

Y: ratio annual Benefit/ Q_ref [€kW^{-1}]

Abbreviations

SHW: Sanitary Hot Water

EES: Engineering Equation Solver

EU: European Union

HP: Heat Pump

HX: Heat exchanger

NxtHPG: Next Generation of Heat Pumps working with Natural Fluids

COP: Coefficient of Performance (HP=heat pump; total=system including the recovery heat exchanger), [-]

Subscripts

HP: Heat Pump

heat: Heat Exchanger

boiler: Gas Boiler

1.-INTRODUCTION

Sustainable energy management as well as environmental protection are two activities of major relevance nowadays. Many efforts towards these objectives have been done and an increase of share of renewable energy is crucial to keep growing in this direction[1].

Under that framework, technologies based on the recovery of low temperature energy sources are becoming an interesting alternatives in the recent years ; its availability linked to the fact that they have not been deeply exploited, make them as promising challenge to keep moving towards a more sustainable world [2]. These sources include from residential (sewage wastewater) to commercial or industrial (condensing loops, wasted heat from thermal processes, thermal power plants). In fact, at this moment most of this heat is wasted to the ambient, is removed by additional technologies (such as refrigeration towers) or is lost to the sewage.

In the residential sector, grey water heat recovery can be a profitable and reliable source of heat according to [3]. In fact, the use of wasted heat from the sewage in order to produce heating, cooling or sanitary hot water (SHW) has demonstrated to be very profitable. Examples of this are in-house or district heating projects [2],[3],[4],[5],[6] and organizations like the Japanese agency which has included it in the strategy for energy efficiency technologies in Japan [7].

Other sectors with a large potential for these type of strategies are the industrial and commercial sectors (power plants, chemical plants, almost any type of industry, hotels, supermarkets, gyms, hospitals…) where there is a huge cooling demand and the heat is dissipated in many situations through a closed condensation loops that, afterwards, needs to be dissipated to the ambient. In these cases, these strategies will lead to additional benefits as in addition to the energy direct use, less heat would be dissipated to the ambient [8],[9],[10]. In addition, the fact that for the most common situations, the heat source use to be water which has a high heat capacity and density and it is under quite constant temperatures (around 20/25°C over the year)[11] allows an optimal sizing design, operating expenses reduction.

At present and regarding the building sector is responsible of around half of global greenhouse emissions, the consumption of two-thirds of all the electricity and one-third of global waste production[11],[12]. To reduce this impact, the main solutions have focused on the reduction of the consumption or the use of more efficient/renewable technologies but mostly regarding to cooling and heating. Prove of this is the reduction of the consumption and, in its extreme, the existence of passive houses with less than 15 $kWhm^{-2}$ of space heating demand[11],[13]. Nevertheless, sanitary hot water has been underestimated and remains a significant constant demand.

In the commercial sector, the heat recovered is used in other processes within the building where there is a water heat need at higher temperature, like in swimming pools, gyms or as combination with solar heating. In this sector, the absorption heat pump -with usual heating COPs around 1.5-2.5 [14]- is one of the most established technologies. Many works are already done in this line, for instance, the use of the wasted heat from a CHP for a spa or as solar-assisted district heating [15], in a textile industry [16] or in desalination plants [17] are examples of this heat source potential.

Conventional technologies to produce SHW in the building and some commercial applications usually operate with low efficiencies or/and high pollutant emissions rate (among others, solar, electric heating, gas and oil boilers) [18]. In this sense, heat pumps are a very promising technology for this application due to its capability to operate with high levels of efficiency, the possible recognition according to the European Directive 2009/28/CE as renewable energy and the capability to use waste water at low temperature as a heat source [19],[20],[21]. Moreover, the use of natural refrigerants in heat pumps for that type of application is quite common. In fact, CO_2 working in transcritical conditions has been demonstrated as a reliable alternative with high COP [20],[21]. In addition others alternatives like propane has demonstrated high levels of performance in this type of applications [22],[23], [24].

Thermodynamically, it is well known that the substitution of the gas boiler by a heat pump is an efficient solution and has the potential of reusing some sources of waste heat. However, up to the knowledge of the authors no public research has been done related to the optimal heat pump size based on the SHW demand and on the waste heat considering, in addition, the economic part which is determinant in the final optimal solution.

In this paper, the optimal substitution of a gas boiler by a heat pump and a recovery heat exchanger (HPR) to produce SHW is analyzed. The study assumes a sanitary hot water demand always larger than the capacity of the HPR, a constant availability and temperature of waste heat that could come from sewage water or a condensation loop. Based on those two conditions, the optimal size of the components that maximize the economic benefit has been analyzed.

The paper is organized as follows: first, a description of the model is presented. Second, the performed analysis section collects the characteristics of the base case study and a sensitivity analysis description. Third, all the results obtained from the model are presented. Finally, the conclusions are discussed.

2.-DESCRIPTION OF THE MODEL

2.1. Description of the system

Figure 1 represents the basic scheme of the water to water heat pump system alone (HPA). Based on the present application, an additional recovery heat exchanger (HPR) in order to pre-heat the water before the inlet of the condenser has been also analyzed (see Figure 2).

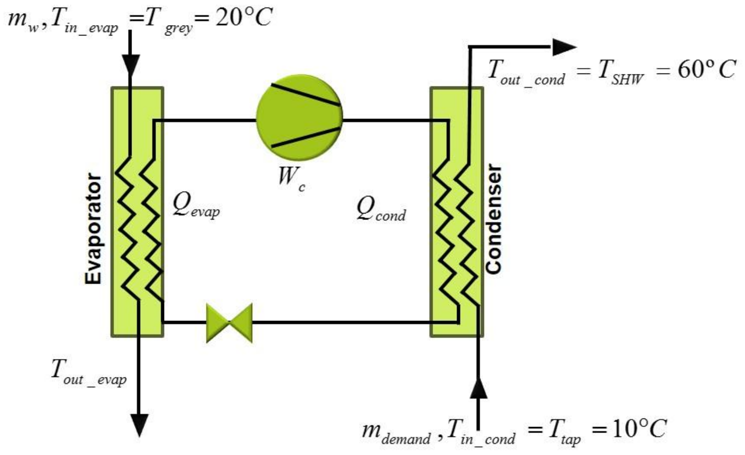

Figure 1: Heat pump alone (HPA) system layout.

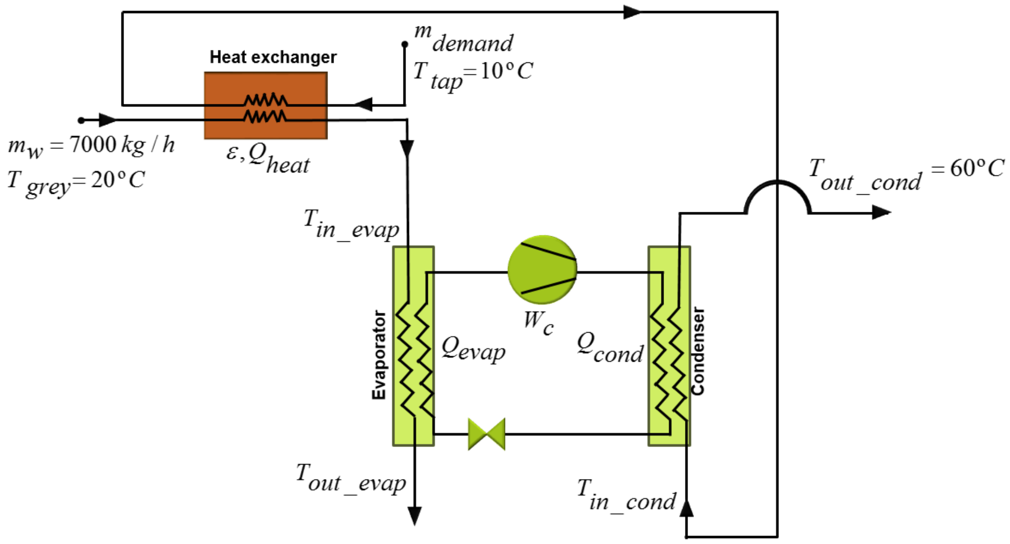

Figure 2: System layout of the heat pump with an additional recovery heat exchanger (HPR)

Characteristics of the heat pump and boundary conditions:

- The system is based on an existing prototype of a new water to water heat pump that is able to work with subcritical conditions and high COPs thanks to the sub-cooling maximization which is adapted based on the operating conditions. Further information as well as a more detailed explanation regarding to the heat pump can be found in [22].
- The nominal heating capacity under the assumptions considered for this study is $Q_{cond} = 42.631 kW$ which is the size of the existing prototype used for the

experimental results and the model validation. In the rest of the document, this value is used as the reference size.

- Refrigerant: the heat pump uses propane not only because of environmentally reasons but also due to interesting thermodynamic characteristics for this application [22], [24].
- Heat source: any available wasted source of energy at low temperature, for instance, sewage water or water from a condensing loop. In this case, water at 20°C and a constant available water mass flow rate of 7000kg h^{-1} has been considered for the base case.
- Sanitary Hot Water production: the SHW demand is assumed to be significantly higher than the production of the heat pump. The tap/fresh water is considered to be at 10°C and it will be heated until 60°C. These are, therefore, the temperature conditions of the condenser.

Characteristics of the recovery plate heat exchanger:

A preliminary study in order to choose a heat exchanger size was done based on the open access Sweep software [25] .

The heat exchanger was chosen with the following boundary conditions based on specifications from the manufacturer:

- Minimum number of plates due to efficient design: 10
- Maximum number of plates due to efficient design: 140

2.2. Model equations

2.2.1. Thermodynamic problem

First, the equations used for the recovery heat exchanger modeling are presented, second, the equations of the heat pump are exposed and third, a description of the model equations of the complete system is done.

The recovery heat exchanger modifies the water temperature at the inlet of the evaporator and condenser of the heat pump. Its influence on the heat pump performance has been evaluated modelling it by the following equations.

The heat rejected from the wastewater is calculated according Eq.1:

$$Q_{heat} = \varepsilon \cdot mcp_{\min} \cdot (T_{grey} - T_{tap}) \tag{1}$$

Where the effectivity has been modeled based on Sweep software[25]. According to that, an expression for the effectivity and the effective capacity as a function of the number of plates and the mass flow rate has been obtained:

$$\varepsilon = f(m_{demand}, Plates) \tag{2}$$

And $mcp_{\min} = \min(m_{demand} \cdot cp_w, m_w \cdot cp_w)$.

The new inlet temperatures are calculated according Eqs.3 and 4:

$$T_{in\_evap} = T_{grey} - \left(\frac{Q_{heat}}{m_w cp_w}\right) \tag{3}$$

$$T_{in\_cond} = T_{tap} - \left(\frac{Q_{heat}}{m_{demand} cp_w}\right) \tag{4}$$

Where T_{in_evap} the evaporator inlet temperature [K] and T_{in_cond} is the condenser inlet temperature [K].

The pressure drop has been calculated following the same methodology described previously for the heat transfer problem and it is shown in Eq. 5 and 6.

$$DP_{demand} = f(m_{demand}, Plates) \tag{5}$$

$$DP_{water} = f(m_w, Plates) \tag{6}$$

The heat pump model is based on empirical correlations for the COP and heating capacity developed from experimental results according to [22] as a function of the water temperature at the inlet of the condenser and the evaporating temperature including the auxiliaries. Eq. 7 and Eq. 8 show the fitting used in the model for an outlet condenser water temperature of 60°C:

$$COP_{hp} = -94.5966685 + 0.22736625 \cdot T_{in\_cond} + 0.39666425 \cdot T_{evap} - 0.00095157 \cdot T_{in\_cond} \cdot T_{evap} \tag{7}$$

$$\begin{aligned} T_{evap} = (&-201.603822 - 17.3859437 \cdot T_{in\_evap} + 19.9534897 \cdot T_{out\_evap} - 0.13609611 \cdot T_{in\_evap}^2 - \\ &- 0.20473267 \cdot T_{out\_evap}^2 + 0.33769076 \cdot T_{in\_evap} \cdot T_{out\_evap}) \end{aligned} \tag{8}$$

$$Q_{cond} = -837.342696 + 1.79739626 \cdot T_{in\_cond} + 3.38242539 \cdot T_{evap} - 0.00725288 \cdot T_{in\_cond} \cdot T_{evap} \tag{9}$$

Where COP$_{hp}$ is the Coefficient of Performance, T_{evap} the evaporating temperature [K], T_{out_evap} [K], the evaporator outlet temperature and Q$_{cond}$ the heating capacity [W].

The water mass flow rate supplied at 60°C (SHW production) is calculated from heat transfer balance according to Eq. 10.

$$m_{demand} = \frac{Q_{cond}}{cp_w (T_{out\_cond} - T_{in\_cond})} \tag{10}$$

The cooling capacity is obtained according Eq. 11:

$$Q_{evap} = Q_{cond} \frac{COP_{hp} - 1}{COP_{hp}} \tag{11}$$

Where Q_{cond} is calculated in Eq.9 and the COP$_{hp}$ from Eq.7.

The compressor capacity is, directly related to the heating capacity and the coefficient of performance according to Eq. 12.

$$W_c = \frac{Q_{cond}}{COP_{hp}} \tag{12}$$

The evaporator outlet water temperature is calculated using Eq.13.

$$Q_{evap} = \dot{m}_w \cdot cp_w \cdot (T_{in\_evap} - T_{out\_evap}) \tag{13}$$

The water pressure drop in the evaporator and the condenser has been calculated based on correlations obtained from experimental results.

The evaporator water pressure drop correlation is shown in the Eq. 14 and Eq. 15

$$DP_{evap} = 2 \cdot 10^{-6} \cdot m_w^2 + 4.1 \cdot 10^{-3} \cdot m_w + 19.962 \tag{14}$$

$$DP_{cond} = 1 \cdot 10^{-5} \cdot m_{demand}^2 + 2.9 \cdot 10^{-3} \cdot m_{demand} + 32.149 \tag{15}$$

Finally, the whole system (Fig. 2) has been defined as a function of COP and the heating capacity by coupling both, the heat exchanger and heat pump. These variables are defined as:

-**COP**:

The auxiliary pump consumption due to the water drop pressures (for both mass flows in the heat exchanger, the evaporator and the condenser) is calculated based on Eq. 16 according to the European standard 14511-3.

$$Power\_pump = \sum \frac{m_k \cdot DP_i}{\eta_{pump} \cdot \rho_w} \tag{16}$$

Where i =[pump_cond, pump_evap, pump_demand, pump_water], $\rho_w = 1000 kgm^{-3}$ the water density , $\eta_{pump} = 0.3$ the pump efficiency and $k = [demand, water]$ respectively.

Therefore, the COP of the HPR system is expressed in Eq.17.

$$COP_{total} = \frac{Q_{heat} + Q_{cond} + P_{pump\_cond}}{W_c + P_{pump\_cond} + P_{pump\_evap} + P_{pump\_demand} + P_{pump\_water}} \quad (17)$$

-**Total Heating Capacit**y:

The total heating capacity supplied by the HPR system is given by Eq.18

$$Q_{HPR} = Q_{heat} + Q_{cond} + DP_{pump\_cond} \quad (18)$$

Thus, the equivalent capacity supplied by the previous gas boiler -the capacity substituted by the heat pump- is calculated according to the European standard 14511-3 expressed in Eq.19

$$Q_f = \frac{Q_{cond} + Q_{heat} + P_{pump\_cond}}{\eta_{cald}} \quad (19)$$

Where $\eta_{cald} = 0.95$ is the considered boiler efficiency.

2.2.2. Economic problem

In order to evaluate the economic benefit, the approach followed in [28] has been used as a reference .

The annual benefit is calculated by the difference between saving and cost according to Eq. 20 considering the annual Saving and the equivalent annual Cost.

$$Benefit = Saving - Cost \quad (20)$$

The cost of an inversion can be divided into three different categories: initial cost, annual cost and operating cost.

- *Initial cost:* includes the investment cost. In the present study, this cost is the heat pump price (function of its size) and the heat exchanger cost (function of the number of plates). Notice that the gas-boiler investment cost will not be considered since the assumption is that there is already gas-boilers operating to warm up the sanitary water and the study only considers the interest of substituting this production by recovering wasted heat through a heat pump.

To calculate the yearly benefit, the equivalent annual cost must be calculated. This term can be understood as if the capital would come from a bank loan under an interest rate, *i,* to be paid off (recovered) in *n* annual payments (years). This is the term considered in "Cost" within the Eq.20.

- *Annual cost:* includes expenses derived from taxes and maintenance. In this work, the same tax rate will be applied annually for the whole scope as well as a fix an annual maintenance cost applies to the heat pump, boiler and the heat exchanger, respectively.
- *Operating cost:* costs derived from the use of the technology. The electricity price in the case of the heat pump and the Natural Gas price in the gas boiler. These prices are based on the tariffs from the company called "Gas Natural Fenosa" at date of 07/06/2016 [27].

Electric price

The price of the chosen Tariff 3.0A which includes an installed power greater than 15kW and a voltage <1kV with 3-periods distinction is expressed in Table 1.

Table 1: Electric tariff

Period	c€/kWh	%of time/day
1	15.5774	42
2	13.0775	33
3	9.5653	25

Another decisive parameter is the time, *t, in which the system has waste heat available and when the system is running.* The study has been done assuming it equal to 8.760h, considering that the wastewater mass flow rate is constant and available during all the hours of the year. The installation is running 24h every day. Hence, a weighted average price of the electricity is considered equals to $C_{elec\_energ} = 0.13249 eurkWh^{-1}$

.

Natural gas price.

The price of the chosen Tariff 3.4. which includes yearly consumption higher than 100MWh is $C_{\_fuel} = 0.04239 eurkWh^{-1}$.

Finally, the term "Saving" includes the annual saving due to the sanitary water production using the heat pump system instead of the gas boiler. It is characterized by the difference between the operating cost of the gas-boiler and of the heat pump system. That is, the cost of the SHW production using a gas boiler for the considered size (natural gas cost and maintenance), the cost of the same production using a heat pump (electric cost and maintenance) and the maintenance cost of the heat exchanger according to Eq. 21.

$$Saving = C_{y\_op\_bo} - C_{y\_op\_HP} - C_{y\_op\_heat} \quad (21)$$

2.2.3. System maximization equation

Once the installation has been characterized, the model optimizes the size of the components based on the maximization of the term "Benefit" presented in the economic part of the modeling in Eq. 20 where the term "Saving" considers the operating costs and the term "Cost" the equivalent annual cost due to the heat pump and the heat exchanger investment cost.

The size of the heat pump and the heat exchanger to obtain the maximum benefit is obtained according to Eq.22.

$$(size, Plates) = f(\max Benefit) \quad (22)$$

Finally, the payback period is calculated as in Eq.23. This term aims to give an overall view of the required number of years to pay the total investment cost (not only under an annual point of view) for the considered life-time of the system and the correspondent originated savings.

Notice that this calculation does not include the actualization of the money but it is a ratio whose components have been previously actualized following the methodology stated in [26].

$$payback(years) = Investment\_\cos t / Saving \qquad (23)$$

Where the term Saving is calculated from Eq.21 and the term Investment cost includes the total investment costs (including taxes).

3. PERFORMED ANALYSIS

The main assumptions performed in the model are summarized in Table 2.

Table 2: Constant parameters in the present work

Wastewater temperature	20°C
Fresh/tap water temperature	10°C
Sanitary hot water demand temperature	60°C
Annual interest rate	3%
Number of plates	10 ≤ Plates ≤ 140
Maintenance gas boiler cost	100 €/year
Maint. Heat pump + heat exchanger cost	150 €/year

The study begins with the analysis of a reference heat available to recover which is calculated according to Eq. 24.

$$Q_{ref} = \dot{m}_w \cdot cp_w \cdot (T_{grey} - T_{out\_evap}) \qquad (24)$$

Where $T_{grey} = 20^{o}C$ and $T_{out\_evap} = 0^{o}C$ (assumed to be the minimum possible temperature at the outlet of the evaporator in order to avoid the water freezing).

Afterwards, a parametric study including values of heat recovered from 5% to 85% of the heat reference has been done. Finally, the sizing of the system is defined by the percentage of heat recovered that leads to the maximum benefit. For that percentage, the size of the components (condenser and heat exchanger) is obtained through the sequence stated in Figure 3.

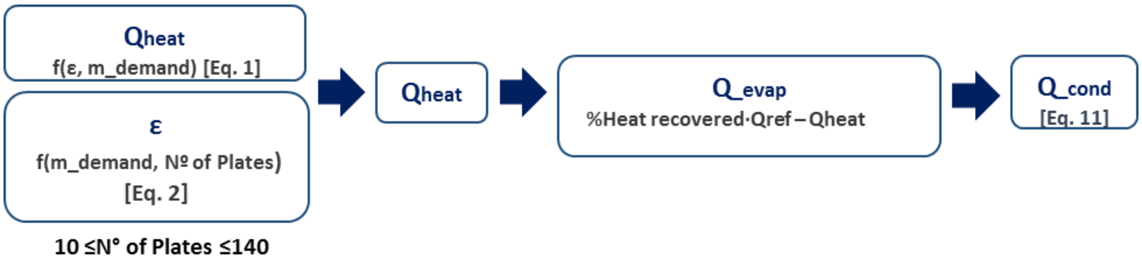

Figure 3: Followed sequence in order to size the system (heat exchanger and heat pump)

In order to dimensionless the problem, the ratio Y=Benefit [eur]/Qreference [kW] has been used in the analysis.

The work is based on a "base case" and its completed with a sensitivity study varying some of the assumptions in order to evaluate different scenarios. The following paragraphs describe the sensitivity cases and the collection of all of them, including the base case, are summarized in Table 4.

- SENSITIVITY ON THE RUNNING HOURS

The different set of variations are the running hours. The Base Case assumes that the installation has a wastewater mass flow of 7000kgs^{-1} at 20°C and a sanitary water consumption greater than the produced by the heat pump during all the hours within a year (24h/day). The second case considers the installation to be working only 12h/day, which is 4380h/year. The third case is based on 8h/day working pattern, 2920h/years and the forth case considers the operation of the installation just 4h/day, a total of 1460h/year.

This sensitivity has been kept for the other parameters variations.

- SENSITIVITY ON THE NUMBER OF PAY-OFF YEARS

The base case study has evaluated the results for 15 years of investment or heat pump life-time since any value is expected afterwards. This parameter conditions the final decision. Therefore, a heat pump life-time of 10 years has also been analyzed.

- SENSITIVITY ON THE ENERGY PRICES

The profitability and attractiveness of this investment, strongly depend on the energy prices. In the base case, the current electric and gas prices have been considered. However, the evaluation of the maximum benefit with higher electricity prices and lower gas prices is interesting.

- Electric price variation: the number “1” means the value considered in the base case. An increase of the tariff price equals to the current peak price has been considered. This is, an increase of 14%.
- Natural Gas price variation: the number “1” means the value considered in the base case. A decrease of the tariff price equals to 4% has been considered. This value is based on the IDAE statistics trend for the past 4 years[28]. In addition, a decrease on the price equals to 14% in order to compare with the electric price variation has been considered.

The sensitivity studies in this section are based on applying a pessimist view regarding to the attractiveness of the heat pump investment. Therefore, only an increase of the electric tariffs and a decrease on the gas prices has been done.

- SENSITIVITY ON THE INVESTMENT COST CONSIDERING DIFFERENT RUNNING HOURS

Finally, the last variable estimated in the study has been the cost of the heat pump and the heat exchanger. The values in the base case are based on a current manufacturer catalogue according to Eq. 26 and 27 named as “1” in the table). The sensitivity is considered as an increase of the 50% in the investment cost (cases 21-24) and a decrease of 50% (cases 25-28).

SENSITIVITY ON THE AVAILABLE SEWAGE WATER MASS FLOW

In the base case, a costant total sewage water mass flow rate of 7000kg/h has been considered through the considered number of operating hours. Different water mass flow rates available would lead to different final benefits but similar sizes at the maximum benefit. In order to demonstrate this approach, the analysis of the system with a sewage water mass flow rate of 14000kg/h and 3500kg/h has been included within this work.

4.-RESULTS AND DISCUSSION

4.1. Study of a heat pump vs system heat exchanger-heat pump

First, an evaluation of the ratio ʒ for the HPA considering the nominal heating capacity and the base case assumptions has been done. The first column of Table 3 collects the results of the maximum benefit case.

Second, the evaluation of the HPR has been performed. Considering the same heat pump size used in the previous case, the evaluation of the profitability by the addition of a heat exchanger based on its size has been performed. This is, the optimization of its area in order to maximize the benefit. The second column of Table 3 contains the results of this case.

Figura 3a represents the evolution of the COP_{hp} and the COP_total with the increase of the heat exchanger area (by means of the increase of the number of plates) adapting to the maximum possible subcooling for every condition. As it can be seen, the COP_{hp} decreases with the increase of the heat exchanger size. The bigger the heat exchange is, the smaller the capacity of the heat pump is.

Figure 3b shows the annual Benefit, the Cost and the Saving according to Eq. 22 and 23 versus the increase of the heat exchanger area. The grey line represents the benefit of the case considering only the heat pump (HPA).

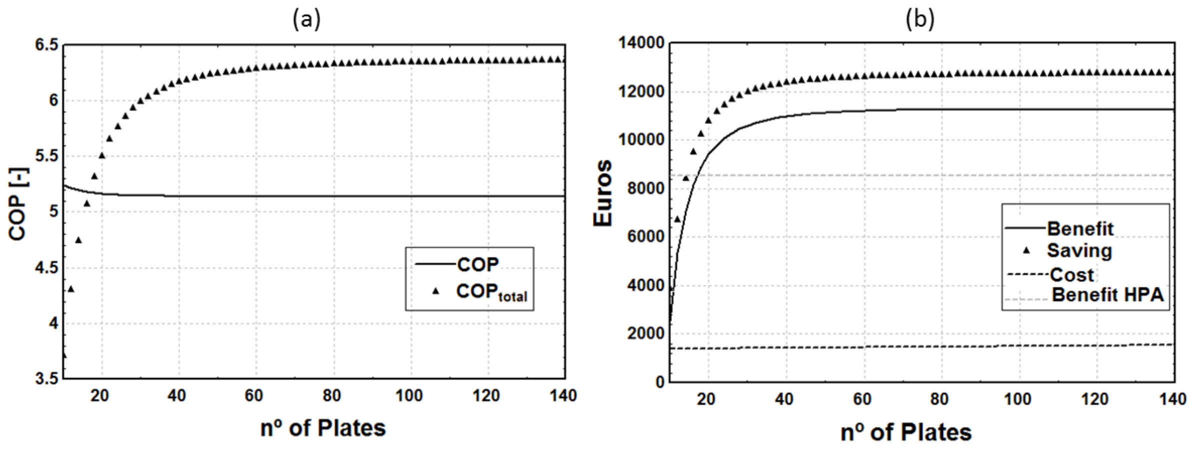

Figure 3: (a) Variation of the COP_{hp} (HPA) and the COP_total (HPR) with the n° of plates of the heat exchanger (b) Variation of the Benefit, Saving and Cost of the system with the n° of plates of the heat exchanger

From (a) and (b) can be inferred that COP_total and the Benefit increases significantly until the effectivity of the heat exchanger becomes almost one (around 80 plates). In this case, the maximum Benefit occurs when using a heat exchanger of 100 plates and it equals to 11,266€ (annually).

The influence of the number of plates in the investment cost is low because it is divided by the number of operation years considered (15years). As in Figure 3 this influence cannot be clearly appreciated due to the scale, Figure 4 represents only the term “Cost” with the addition of number of plates and it increases from 1400eur/years to 1550 eur/years. This term is an annual term that considers the investment cost, the maintenance cost and the operating cost.

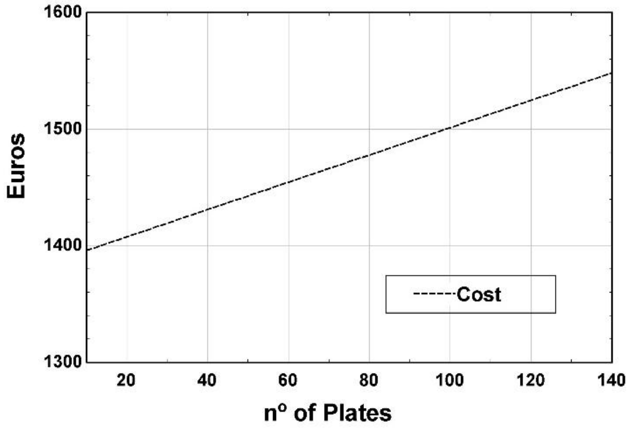

Figure 4: Cost evolution for a heat pump size of one and the variation of the number of plates of the recovery heat exchanger.

Table 3 collects the main thermos and economic parameters for the optimal case.

Table 3. Output of the system (heat pump + heat exchanger) case

	Heat pump	Heat pump + Heat exchanger
Q ref (kW)	162.556	162.556
% of heat recovered	23.45 %	27.53 %
THERMODYNAMIC VARIABLES		
Tin_cond (°C)	10	19.81
Tout_cond (°C)	60	60
Tin_evap (°C)	20	18.72
Tout_evap (°C)	15.31	14.49
Q_cond (kW)	42.63	42.63
Wc (kW)	8.2	8.2
Q_heat (kW)	-	10.41
COP_{hp}	5.66	5.142
COP_total	5.649	6.356
mw (kg/h)	7000	7000
m_demand (kgh^{-1})	798	913.68
ECONOMIC RESULTS		
Annual equivalent cost (€)	1351	1501
Annual saving (€)	9973	12767
Annual benefit (€)	8622	11266
Y (€/kW)	53.04	69.3
Payback (years)	1.62	1.37

From Table 3 can be said that the substitution of the SHW production from a gas boiler to a heat pump is very profitable. The annual benefit is 8622€ with a COP_total, of 5.649. This means that, asking for a bank loan with 3% of interest the investment cost on a heat pump, the payoff to the bank would be 1351€ annually during 15 years while you will be saving 9973€, leading to a benefit of 8622€ during the considered life-time.

The investment on the system composed by the heat pump and the heat exchanger (HPR) brings considerably more profitability than the heat pump itself. Specifically, the benefit for the best case is 23.4% higher. The benefit of the HPR is higher than the benefit of the HPA when the number of plates is greater than 18, even if it is not the optimum.

Based on these results, the HPR has demonstrated a greater performance than the HPA. Therefore, now the size of the heat pump as well as the recovery heat exchanger are studied in order to be optimized.

4.2. Study of the optimal size of HPR to maximize the Benefit.

The analyisis of each case consists of:

- Evaluation of the COP_total
- Estimation of the Benefit
- Optimal size that maximizes the benefit

4.2.1. Base Case

Figure 5a represents the COP_hp as a function of the percentage of energy recovered and the number of plates. Grey color corresponds to the highest value and it is found with low values of number of plates in the heat exchanger and relatively low percentages of heat recovered. This result can be related to the size of the heat pump. Moreover, the variation has more influence in the COP than in the number of plates. The maximum COP_hp (5.3) is found for values of heat recovered around 15% which means heating capacities around 25kW and only 20 plates considering HPR. Nevertheless, it is worthy to notice that the maximum COP_hp is 5.767 and it occurs for the HPA of the same size as the considered in the system.

Figure 5b represents the COP_total as a function of the percentage of energy recovered and the number of plates. Grey color corresponds to the highest value. The COP_total increases as the percentage of heat recovered decreases and with the addition of plates (higher UA values). It should be noticed that the optimal number of plates depends on the heat exchanger effectivity and hence, the trend is not linear. The maximum values correspond to large heat exchangers and relatively small heat pump sizes. Thermodynamically, this can be explained as the COP_total takes into account both components of the system, the heat exchanger (which exchanged heat is given "for free") and the heat pump. The maximum COP_total is around 6.51 and occurs for the maximum heat exchanger size and the most efficient (in terms of COP) heat pump which, according to figure 5a, corresponds to a heating capacity around 25kW.

Figure 5c represents the ratio Y[€/kW] = Benefit/Qref as a function of the percentage of heat recovered and the number of plates. Grey color corresponds to the highest benefit. The maximum values of Y occur when the percentage of heat recovered is located around 50% and increases with the addition of plates to the heat exchanger until around 80 number of plates from when the ratio becomes very similar according to the effectivity of the heat exchanger curve. It is noticeable that maximum benefit ratio (Y >100€/kW) does not correspond to the maximum COP_ total, this fact means that other considerations like the investment cost and the energy produced with it, among others, must be considered in order to determinate the most profitable solution. In this case, the increase of the HPR capacity leads to higher operational savings despite of the increment of the investment.

From figure 5c it can be extracted that values of 103€/year per kW of heat recovered by the substitution of a gas boiler by a heat pump of 82.45kW and a heat exchanger of 19.6kW can be obtained.

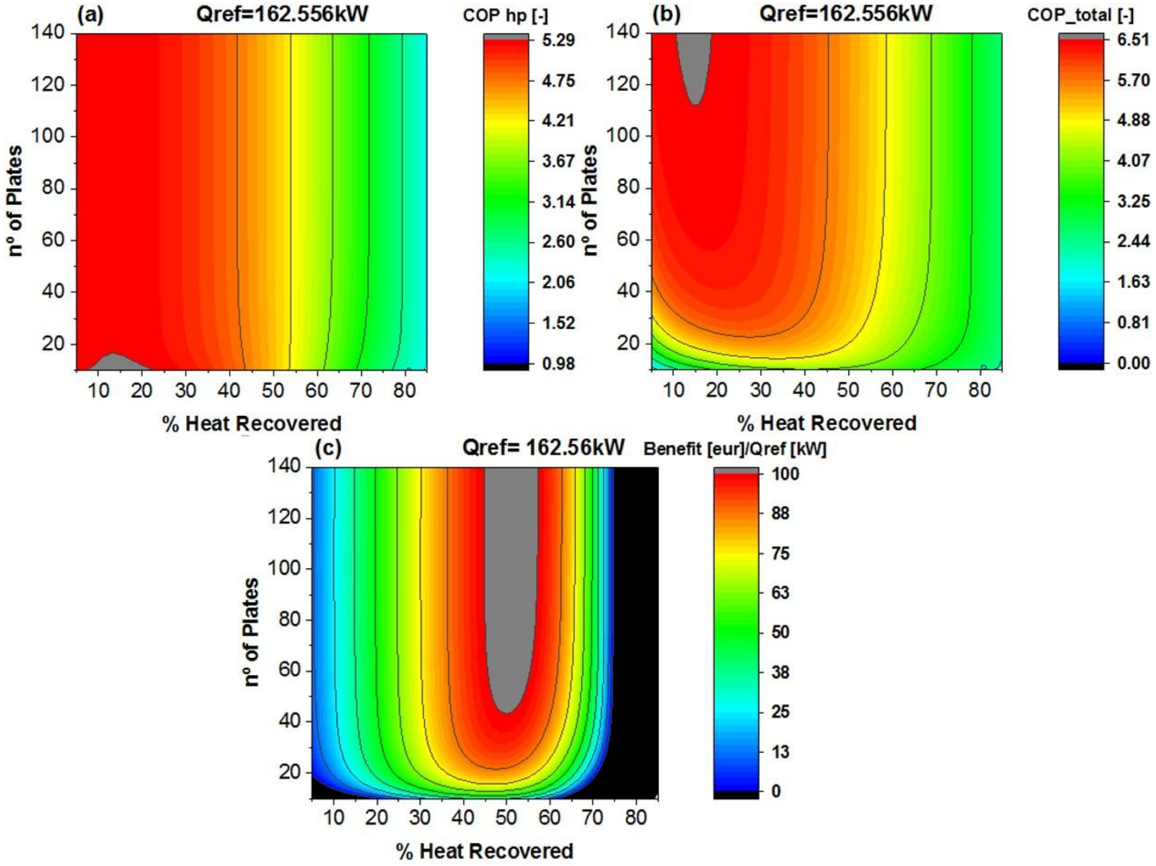

Figure 5: (a) COP variation function of the percentage of heat recovered and number of plates. Base case. (b) COP_total variation function of the percentage of heat recovered and number of plates. Base case. (c). Y=Benefit/Qref variation function of the percentage of heat recovered and number of plates. Base case.

Figure 6a presents the variation of the ratio annual investment cost of the HPR/Qref as a function of the heat pump and the percentage of heat recovered. The term annual investment cost is the total investment cost in yearly values including the annual interest rate. As it can be observed, the investment cost increases with the percentage of heat recovered (bigger HPA) and with the number of plates. The heat exchanger investment cost, has major contribution as the heat pump is smaller. The total investment cost increases with the number of plates proportionally much more for values of heating recovered lower than 40% than for higher recovered values where the increase of the size in the heat exchanger becomes much less important in the total investment cost.

Figure 6b presents the variation of the ratio saving/Qref as a function of the heat pump and the percentage of heat recovered. The saving includes the operating costs of both, the HPR and the gas boiler. Similar trend as in Figure 5c for the benefit can be observed. As the percentage of heat recovered increases the saving term rises until a maximum which corresponds to a values around 55% of heat recovered and saving rate of more than 125€/kW recovered. With the increase of the HPR size, the COP_total decreases (Figure 5b) and the consumption of the compressor with the auxiliaries increases, reaching values of the saving that can be even negative.

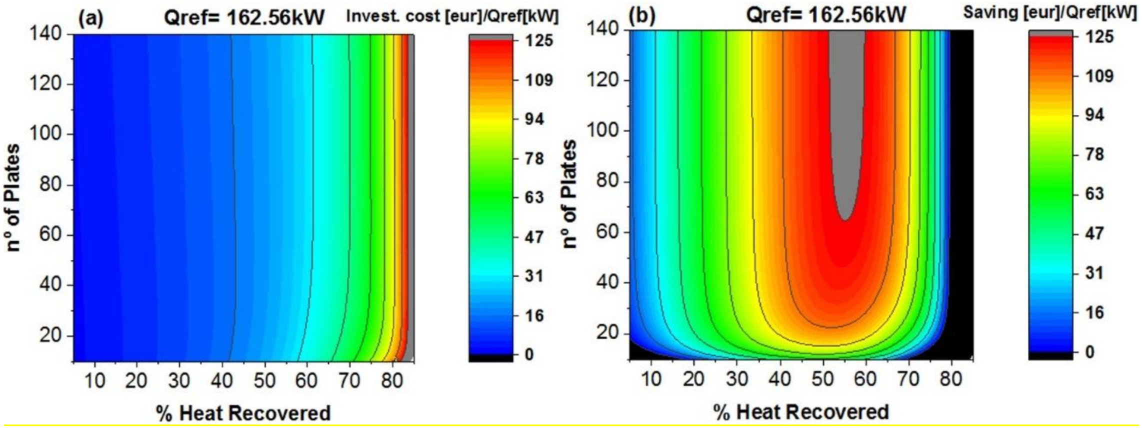

Figure 6: (a)Annual investment cost of the system/Qref function of the percentage of heat recovered and the number of plates for the base case. (b) Saving/Qref of the system function of the percentage of heat recovered and the number of plates for the base case.

Figure 7 represents the variation of the ratio heating capacity/Qref with the number of plates and the percentage of heat recovered. This figure allows to have an idea about the sizes of the heat pump for the base case. As it can be seen in the figure, the size of the HPA increases as the percentage of heat recovered increases. Regarding to the number of plates, the size of the HPA depends on the effectivity of the heat exchanger curve: being needed for the same percentage of heat recovered a larger HPA when the number of plates is low (small HE) and remaining practically constant once the effectivity achieves values close to one (from 80 plates). This effect is more important as the size of the HPA increases.

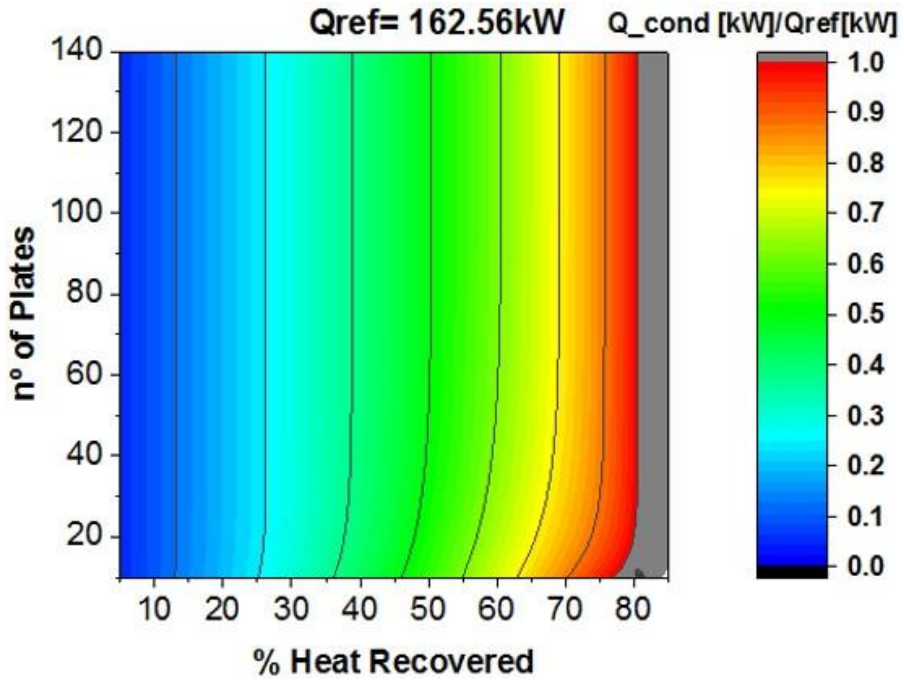

Figure 7: Heat pump size/Qref function of the percentage of heat recovered and the number of plates for the base case.

4.1.1. Cases 1-4

These cases represent the study of the operating hours influence on the final benefit. The reference heat for the cases 1-27 is 162.56kW which corresponds to an available water mass flow rate from the sewage of 7000kg/h. Figure 8 shows the variation of the ratio Y[€/kW] = Benefit/Qref with the percentage of heat recovered and number of plates of the heat exchanger for different available operating hours. Grey color corresponds to the highest benefit and black color to negative values of the benefit.

According to the figure, as the operating time is larger, the optimal size of the heat exchanger and the heat pump size increase and the annual benefit is higher. Nevertheless, in terms of percentage of heat recovered, values around 50% lead to the best solution from a certain number of operating hours. The annual investment cost becomes more important as the number operating hour decreases. The same investment size could lead to a benefit (>16000eur) if the installation is used 24h/days (51% of heat recovered) or could lead to a not profitable investment (negative benefit) for example if the installation is used only 4h/day. Therefore, the effect of the operating hours is determinant. Thus, a critical variable when trying to find the optimal size of these systems is the availability and the use that the system will have.

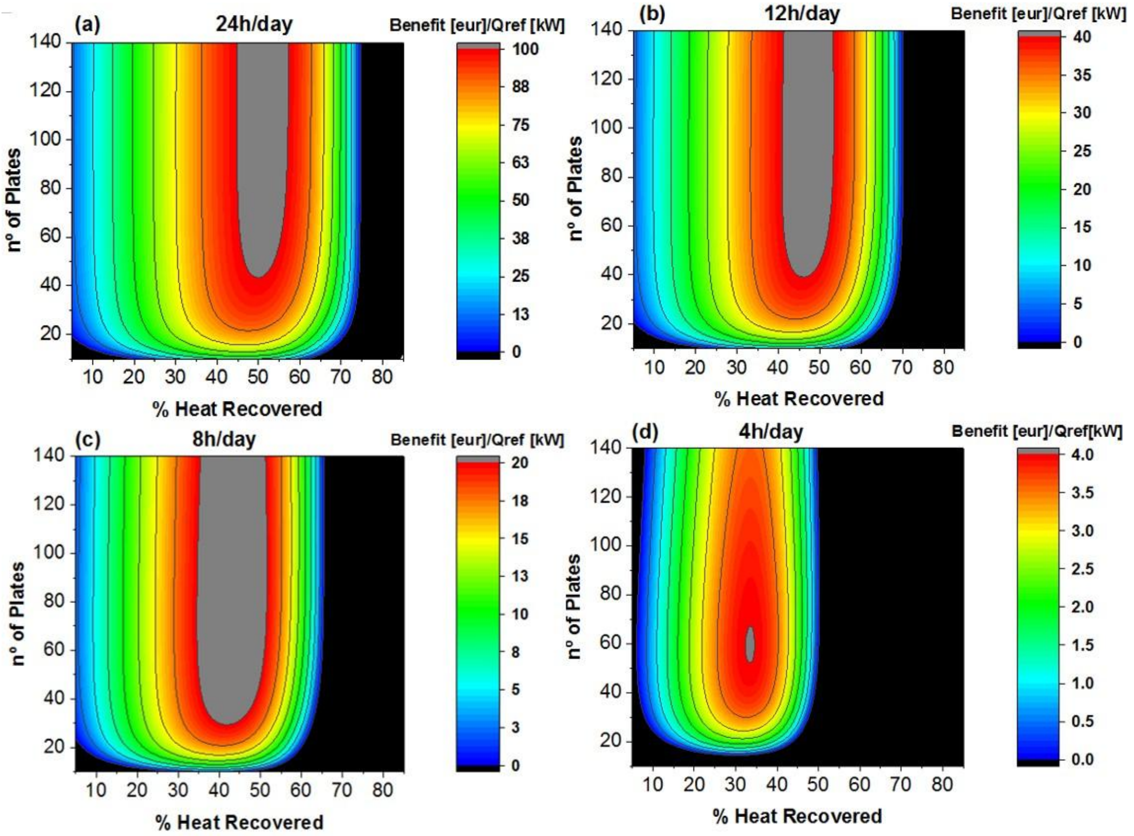

Figure 8: Y=Benefit/Qref variation function of the percentage of heat recovered and number of plates. (a) Base case (24h/day); (b) 12h/day; (c) 8h/day; (d) 4h/day. The colors of the scale have not been maintained across the graphs due to scale differences.

It should be noticed that the COP_total increases with the diminution of the HPA size. However, based on the electricity and gas price assumptions, the influence of the production volume on the annual benefit becomes more important as the size increases. While the benefit from using the installation 24h/day to the lowest use (4h/day) is reduced around 96%, the SHW production capacity reduces 37%.

Table 5 collects the main thermodynamic, economic and the optimal sizes of the maximum benefit for all the cases.

4.1.2. Cases 5-28

The rest of the sensitivity study is presented only for the optimal solution in order to be able to have an overall view of the results summarized in Table 5.

Figure 9 represents the maximum ratio Y=Benefit/Qref in monetary terms for each case. The horizontal lines are the maximum benefits for the operating hours considered in the base case.

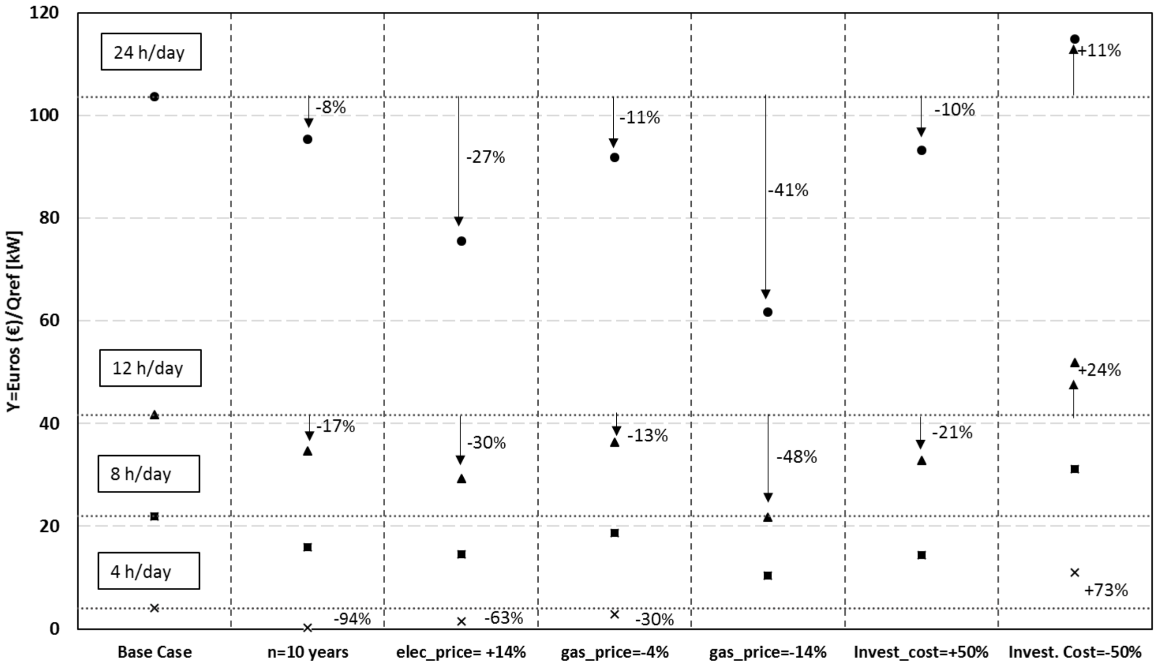

Figure 9: Maximum ratio Benefit/Qref of any studied case based on the number of operating hours.

The 14% decrease on the gas price is the most influent parameter followed by the increase on the electricity price as well as the decrease of 4% on the gas price, except for low operation hours represented by last series (4h/day). Therefore, in general, the most influent effect on the maximum benefit is the electricity/gas price. Their volatility as well as the dependency on external factors make the investment decision riskier. However, from a determined number of operating hours, all the cases experiment high benefits by the substitution of the SHW production from a gas boiler to a heat pump.

Regarding to the investment cost influence and considering that the cost of the heat pump and the heat exchanger were conservative in the base case, even increasing it by 50%, the investment would still be profitable.

According to the followed approach, the investment cost is divided by “annual equivalent” quantities as if a loan were asked to the bank. The time in which this “loan” must be returned as well as the interest rate of it is also an important variable. In this study, a 3% of interest rate has been considered (pessimistic rate with the current bank situation) a 15 years’ period (also pessimistic due to the heat pump lifetime is expected to be higher than 15). Nevertheless, even if the study is made for 10 years of lifetime, the investment reminds highly beneficial.

Figure 10a represents the optimal heat pump size (heating capacity kW) for each case and operating hours.

The more operating hours, the higher savings and benefits. Thus, bigger sizes of the heat pump (it is shown by the upper dots).

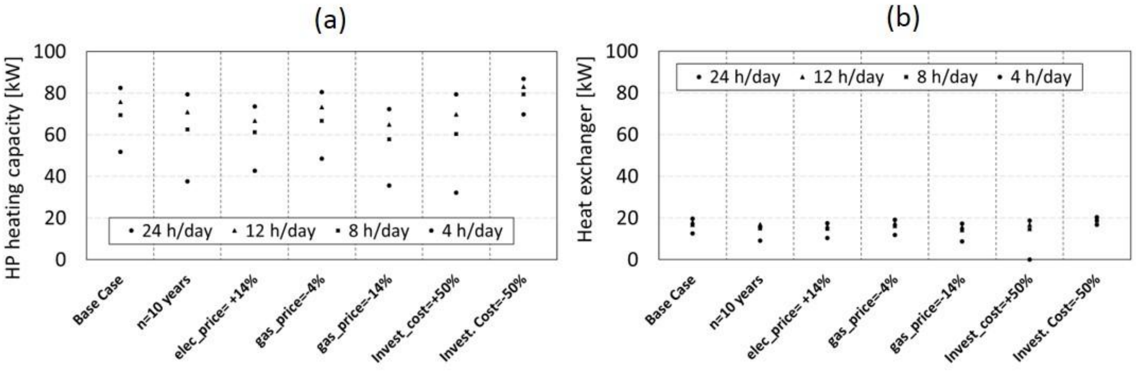

Figure 10: (a) Optimal heat pump heating capacity of every considered case (b) Optimal heat exchanger capacity for every considered case.

The optimal size of the heat pump strongly depends on external variables like the grey water temperature, the gas and electric price, the investment cost and the like. Nevertheless, if the operating hours is greater than 4.1h/day, the substitution of a gas boiler by a heat pump is profitable even under a wide range of conservative conditions according to the results of this study.

Figure 10b represents the optimal number of plates of the recovery heat exchanger for each case. The optimal number of plates of the heat exchanger is mainly influenced by the investment cost and the use of the installation. In any case, the maximum benefit occurs with a medium/high number of plates which result for the considered heat exchanger of capacities around 18kW for most of the considered cases.

It should be noticed that the optimum recovery heat exchanger depends mainly on the operation hours. Hence, defined this parameter, a good estimation of the optimal size can be done.

Finally, Figure 11 represents the payback period of the optimal investment for the considered life-time (15 years except for the case that is 10 years).

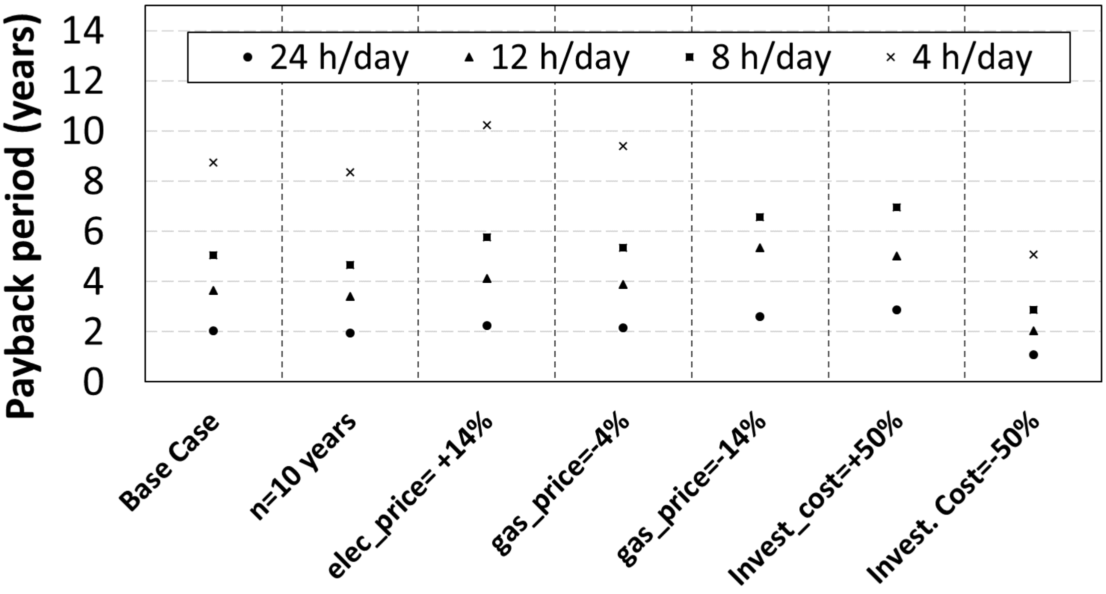

Figure 11: Payback time for every considered case

As it can be seen from the figure, the payback period depends on the number of life-time considered for the system and indirectly on the number of operating hours. However, the frame of the payback time is narrow (from a considerable number of operating hours, the expected payback time varies from 2-6 years).

4.1.3. Cases 29-30

The last sensitivity case is the study of the influence of the available water mass flow rate (sewage mass flow rate) in the most profitable solution. Two more available mass flow rates have been considered within this cases: half of the base case water mass flow rate (3500kg/h) and double (14000kg/h).

Figure 12 represents the rate Benefit/Qref obtained for (a) 3500kg/h and (b) 14000kg/h of available sewage mass flow rate function of the percentage of heat recovered and the number of plates.

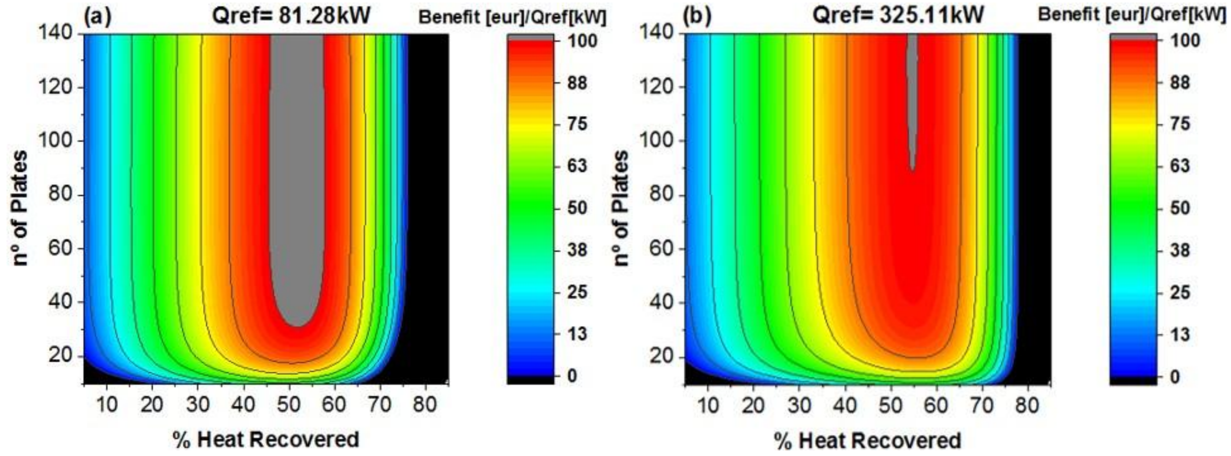

Figure 12: Ratio Benefit/Qref variation function of the percentage of heat recovered and number of plates. (a)mw= 3500kg/h,(b)mw=14000kg/h.

As it can be observed from Figure 12, the maximum benefit states around the same percentage of heat recovered (50-55%) in both cases according to what happens also for the base case (8760kg/h) in Figure 5c. Therefore, the heat available influences the final annual benefit obtained but not the ratio (which is very similar in the three cases) and not the maximum value (which is located for very similar percentages of heat recovered). The number of plates that lead to that maximum benefit states around 80 for the three cases. In addition, the variation of the benefit across the number of plates for the respective percentage of heat recovered has a very flat slope, not penalizing very much in the final benefit. This can be seen for the base case in Figure 13.

Figure 13 represents the variation of the benefit with the number of plates for the base case and the percentage of heat recovered of 51.06% which corresponds to the highest benefit.

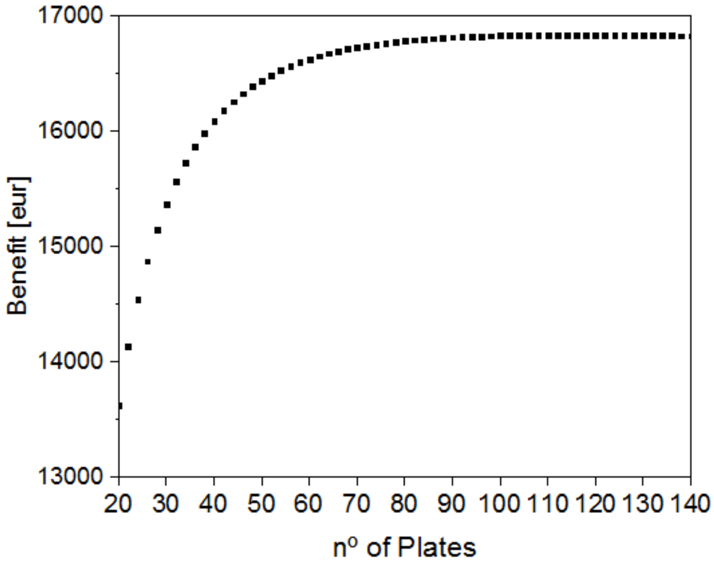

Figure 13: Benefit variation with the number of plates for the base case and 51.06% of recovered heat.

5.- CONCLUSION

In this work, an analysis of the potential profitability derived from the substitution of the SHW production from a conventional technology (gas boiler) to a new heat pump booster to recover heat from a low temperature water source has been done.

This analysis consists of an optimization of the heat pump size to maximize the benefit.

The main conclusions of this work are:

- The introduction of a recovery heat exchanger is always positive.
- As a consequence of the number of external variables required in order to find the optimal solution of this kind of system, a sensitive analysis of the influence of the different variables involved in the process has been done. From that, it has been determined that as far as the number of operating hours are greater than 1500 within a year, the investment reminds clearly profitable, even under the hypothesis of

considering a 14% variation in gas/electricity prices, 50% of variation in the investment cost and a 33% of the reduction in the heat system lifetime. Therefore, the heat pump demonstrates that is a very interesting and cost effective technology for this type of applications.

- The size that corresponds to the maximum benefit of the recovery heat exchanger, the heat pump as well as the payback period depends mainly on the operating hours.
- The maximum benefit of the system strongly depends on the properly sizing of it. It is worth it to notice that the maximum benefit does not take place for a heat pump size with the highest benefit but to a size that optimizes the whole system (the heat pump and the heat exchanger) for a given external conditions.
- Results for the base case show that the substitution of the gas boiler by the heat pump can lead to annual benefits of around 103€/kW of heat recovered and this ratio remains very similar with the variation of the available water mass flow rate from the sewage to recover.

Finally, from all this work it has been proved that the system composed of a heat pump booster with a recovery heat exchanger has great potential to substitute conventional technologies as for instance boilers, to produce SHW. The accurate sizing of the system is crucial to obtain the maximum benefit.

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Table 4. Parameters variation. Base and sensitivity cases.

CASE NUMBER	MW [Kg/h]	INVESTMENT COST [€]	GAS PRICE [€/kWh]	ELECTRIC PRICE [€/kWh]	PAY-OFF YEARS [years]	RUNNING HOURS [h]
1 BASE CASE	7000	1	0.04239	0.13249	15	8760
2	1	1	1	1	15	4380
3	1	1	1	1	15	2920
4	1	1	1	1	15	1460
5	1	1	1	1	10	8760
6	1	1	1	1	10	4380
7	1	1	1	1	10	2920
8	1	1	1	1	10	1460
9	1	1	1	+14%	15	8760
10	1	1	1	+14%	15	4380
11	1	1	1	+14%	15	2920
12	1	1	1	+14%	15	1460
13	1	1	-4%	1	15	8760
14	1	1	-4%	1	15	4380
15	1	1	-4%	1	15	2920
16	1	1	-4%	1	15	1460
17	1	1	-14%	1	15	8760
18	1	1	-14%	1	15	4380
19	1	1	-14%	1	15	2920
20	1	1	-14%	1	15	1460
21	1	1.5	1	1	15	8760
22	1	1.5	1	1	15	4380
23	1	1.5	1	1	15	2920
24	1	1.5	1	1	15	1460
25	1	0.5	1	1	15	8760
26	1	0.5	1	1	15	4380
27	1	0.5	1	1	15	2920
28	1	0.5	1	1	15	1460
29	3500	1	1	1	1	1
30	14000	1	1	1	1	1

Table 5. Summary of the main results for the base and the sensitivity cases.

CASE NUMBER	Tin_cond (°C)	Tout_cond (°C)	Tin_evap (°C)	Tout_evap (°C)	Tevap (°C)	Qref (kW)	Qrecovered (%)	Q_heat (kW)	COP	COP_total	m_demand (kg/h)	Annual equivalent cost (€)	Annual saving (€)	Y(€/kW) Annual Benef/Qref	Heat pump size (kW)	Nº of plates	Payback (years)
1	19.55	60	17.59	9.721	0.99	162.56	51.06	19.6	4.34	5.35	1768.7	3459	20299	103.593	82.45	110	2.04
2	19.6	60	17.79	10.53	2.586	162.56	47.35	17.97	4.52	5.58	1613.16	2974	9751	41.695	75.76	88	3.64
3	19.64	60	17.96	11.26	3.87	162.56	43.79	16.55	4.68	5.761	1476	2608	6171	21.918	69.45	76	5.046
4	19.76	60	18.45	13.33	6.746	162.56	33.28	12.6	5.01	6.144	1112.4	1804	2456	4.012	51.87	58	8.76
5	19.57	60	17.67	10.04	1.637	162.56	49.44	15.5	4.42	5.45	1707.5	4563	20058	95.325	79.48	102	1.94
6	19.63	60	17.92	11.09	3.569	162.56	44.6	16.9	4.64	5.72	1510.92	3770	9413	34.713	70.85	80	3.417
7	19.69	60	18.16	12.11	5.181	162.56	39.75	14.93	4.83	5.94	1326.24	3142	5729	15.914	62.55	66	4.67
8	19.83	60	18.88	15.18	8.356	162.56	24.39	9.105	5.2	6.318	797.76	1758	1795	0.227	37.68	52	8.35
9	19.63	60	17.85	10.8	3.072	162.56	46.21	17.49	4.58	5.66	1563.5	15139	2864	75.511	73.65	110	2.26
10	19.67	60	18.02	11.51	4.27	162.56	42.17	15.99	4.72	5.827	1433.88	2512	7275	29.300	66.63	86	4.12
11	19.71	60	18.19	12.25	5.38	162.56	38.94	14.75	4.85	5.979	1301.4	2201	4570	14.573	61.17	74	5.75
12	19.81	60	18.72	14.49	7.863	162.56	27.63	10.41	5.14	6.297	913.68	1455	1694	1.473	42.78	60	10.25
13	19.57	60	17.65	9.99	1.544	162.56	38.29	19.074	4.40	5.433	1716.5	3297	18213	91.763	80.57	110	2.16
14	19.62	60	17.85	10.8	3.073	162.56	35.25	17.436	4.58	5.652	1563.12	2839	8738	30.173	73.30	88	3.88
15	19.67	60	18.04	11.57	4.373	162.56	32.35	15.96	4.73	5.832	1422	2471	5498	18.621	66.69	74	5.36
16	19.78	60	18.55	13.76	7.2	162.56	23.95	11.8	5.06	6.205	1038.6	1669	2122	2.789	48.52	58	9.39
17	19.64	60	17.88	10.91	3.269	162.56	45.47	17.269	4.60	5.687	1542.96	2801	12823	61.651	72.39	102	2.61
18	19.69	60	18.08	11.77	4.674	162.56	41.11	15.602	4.77	5.882	1387.08	2397	6079	22.650	64.89	80	5.35
19	19.73	60	18.28	12.61	5.878	162.56	36.95	13.98	4.91	6.049	1237	2063	3754	10.402	57.87	72	6.56
20	19.84	60	18.93	15.39	8.477	162.56	23.06	8.719	5.21	6.359	763.2	1209	1204	-0.030	35.61	58	-
21	19.58	60	10.13	10.1	1.824	162.56	49.41	18.78	4.44	5.472	1689.12	4806	19945	93.135	79.48	100	2.88
22	19.64	60	17.95	11.2	3.769	162.56	44.01	16.67	4.66	5.748	1489.32	3957	9301	32.880	69.85	78	5.01
23	19.71	60	18.21	12.32	5.482	162.56	38.38	14.52	4.86	5.98	1288.44	3243	5576	14.352	60.27	64	6.97
24	10	60	20	16.73	9.616	162.56	16.35	0	5.75	5.743	554.4	1379	1346	-0.201	32.17	0	-
25	15.52	60	17.48	9.305	0.122	162.56	53.46	20.462	4.24	5.226	1850.76	1881	20560	114.911	86.95	138	1.09
26	19.55	60	17.59	9.721	0.998	162.56	51.4	19.601	4.34	5.351	1768.7	1728	10148	51.796	83.11	108	2.03
27	19.58	60	17.69	10.13	1.824	162.56	49.35	18.78	4.43	5.472	1689.12	1602	6648	31.047	79.36	100	2.87
28	19.64	60	17.95	11.2	3.769	162.56	44.01	16.67	4.66	5.748	1489.32	1319	3100	10.962	69.85	78	5.08
29	19.82	60	17.5	9.626	0.8695	81.28	51.87	10.17	4.32	5.35	892.44	1789	10204	103.531	41.63	80	2.09
30	18.55	60	17.92	10.11	1.554	325.11	49.46	33.81	4.44	5.345	3405.96	6519	39070	100.120	163.9	126	1.99

TITLE:

Optimal sizing of a heat pump booster for sanitary hot water production to maximize benefit for the substitution of gas boilers

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ABSTRACT

Heat recovery from water sources such as sewage water or condensation loops at low temperatures (usually between 10-30°C) is becoming very valuable. Heat pumps are a potential technology able to overcome the high water temperature lift of the Sanitary Hot Water (SHW) application (usually from 10°C -60°C with COPs up to 6). This paper presents a model to find the optimal size of a system (heat pump and recovery heat exchanger) based on water sources to produce SHW compared to the conventional production with a gas boiler in order to maximize the benefit. The model includes a thermal and economic analysis for a base case and analyzes the influence of a wide set of parameters which could have a significant influence. Even the uncertainties involved, results point out considerable benefits from this substitution based on the capacity of the system. Thus, demonstrating the importance of the optimal size analysis before an investment is done.

Keywords: heat pumps, sanitary hot water, waste water, low grade heat recovery, optimal size

NOMENCLATURE

m_{demand}: SHW mass flow rate capacity, tap water flow [kg s^{-1}]

m_w: wastewater mass flow rate [kg s^{-1}]

cp_w: specific water heat [J kgK $^{-1}$]

T_{grey}: wastewater temperature [ºC]

T_{tap}: fresh/tap water temperature [ºC]

T_{in_evap} : evaporator water inlet temperature [ºC]

T_{out_evap} : evaporator water outlet temperature [ºC]

T_{in_cond} : condenser water inlet temperature [ºC]

T_{out_cond} : condenser water outlet temperature [ºC]

T_{evap} : fluid evaporating temperature [ºC]

W_c :compressor consumption [kW]

Q_{ref} : available heat to recover assuming a lowest water temperature of 0°C [kW]

Q_{evap}: cooling capacity [kW]

Q_{heat}: heat exchanged in the heat exchanger [kW]

Q_f : fuel heating capacity [kW]

ε: heat exchanger effectiveness

DP_{evap} : water drop pressure through the evaporator [mbar]

DP_{cond} : water drop pressure through the condenser [mbar]

DP_{demand} : fresh water drop pressure through the HE [mbar]

DP_{water} : wasted water drop pressure through the HE [mbar]

$Power\_pump$: consumption of the water pump [kW]

η_{pump} : pump efficiency [-]

ρ_w : water density [kg (m3)$^{-1}$]

η_{cald} : boiler efficiency [-]

Economic

i : bank interest rate [%]

n : annual payments [years]

r : annuity [-]

$C_{y\_total\_m}$: Annual equivalent investment cost of *m* [€ year^{-1}]

C_{a_m} : Annual cost of the element *m* [€ year^{-1}]

C_{y_m} : Yearly costs of *m* related to taxes [€ year^{-1}]

C_{i_m} : Initial investment cost of *m* function of its size [€]

C_{s_m} : Residual value of *m* after the *n* years [€]

$C_{y\_op\_m}$: Annual operating cost of *m* [€ year^{-1}]

C_{elec_energ}: electricity price (energy term) [€ kWh^{-1}]

C_{elec_pow}: electricity price (power term) [€ kW^{-1}]

C_{maint_k}: annual maintenance cost of *m* [€ year^{-1}]

$C_{\_fix\_gas}$: fix part of the gas price [€ year^{-1}]

$C_{\_fuel}$: gas price [€ kWh^{-1}]

t: operating hours of the installation [h]

Y: ratio annual Benefit/ Q_ref [€kW^{-1}]

Abbreviations

SHW: Sanitary Hot Water

EES: Engineering Equation Solver

EU: European Union

HP: Heat Pump

HX: Heat exchanger

NxtHPG: Next Generation of Heat Pumps working with Natural Fluids

COP: Coefficient of Performance (HP=heat pump; total=system including the recovery heat exchanger), [-]

Subscripts

HP: Heat Pump

heat: Heat Exchanger

boiler: Gas Boiler

1.-INTRODUCTION

Sustainable energy management as well as environmental protection are two activities of major relevance nowadays. Many efforts towards these objectives have been done and an increase of share of renewable energy is crucial to keep growing in this direction[1].

Under that framework, technologies based on the recovery of low temperature energy sources are becoming an interesting alternatives in the recent years ; its availability linked to the fact that they have not been deeply exploited, make them as promising challenge to keep moving towards a more sustainable world [2]. These sources include from residential (sewage wastewater) to commercial or industrial (condensing loops, wasted heat from thermal processes, thermal power plants). In fact, at this moment most of this heat is wasted to the ambient, is removed by additional technologies (such as refrigeration towers) or is lost to the sewage.

In the residential sector, grey water heat recovery can be a profitable and reliable source of heat according to [3]. In fact, the use of wasted heat from the sewage in order to produce heating, cooling or sanitary hot water (SHW) has demonstrated to be very profitable. Examples of this are in-house or district heating projects [2],[3],[4],[5],[6] and organizations like the Japanese agency which has included it in the strategy for energy efficiency technologies in Japan [7].

Other sectors with a large potential for these type of strategies are the industrial and commercial sectors (power plants, chemical plants, almost any type of industry, hotels, supermarkets, gyms, hospitals…) where there is a huge cooling demand and the heat is dissipated in many situations through a closed condensation loops that, afterwards, needs to be dissipated to the ambient. In these cases, these strategies will lead to additional benefits as in addition to the energy direct use, less heat would be dissipated to the ambient [8],[9],[10]. In addition, the fact that for the most common situations, the heat source use to be water which has a high heat capacity and density and it is under quite constant temperatures (around 20/25°C over the year)[11] allows an optimal sizing design, operating expenses reduction.

At present and regarding the building sector is responsible of around half of global greenhouse emissions, the consumption of two-thirds of all the electricity and one-third of global waste production[11],[12]. To reduce this impact, the main solutions have focused on the reduction of the consumption or the use of more efficient/renewable technologies but mostly regarding to cooling and heating. Prove of this is the reduction of the consumption and, in its extreme, the existence of passive houses with less than 15 $kWhm^{-2}$ of space heating demand[11],[13]. Nevertheless, sanitary hot water has been underestimated and remains a significant constant demand.

In the commercial sector, the heat recovered is used in other processes within the building where there is a water heat need at higher temperature, like in swimming pools, gyms or as combination with solar heating. In this sector, the absorption heat pump -with usual heating COPs around 1.5-2.5 [14]- is one of the most established technologies. Many works are already done in this line, for instance, the use of the wasted heat from a CHP for a spa or as solar-assisted district heating [15], in a textile industry [16] or in desalination plants [17] are examples of this heat source potential.

Conventional technologies to produce SHW in the building and some commercial applications usually operate with low efficiencies or/and high pollutant emissions rate (among others, solar, electric heating, gas and oil boilers) [18]. In this sense, heat pumps are a very promising technology for this application due to its capability to operate with high levels of efficiency, the possible recognition according to the European Directive 2009/28/CE as renewable energy and the capability to use waste water at low temperature as a heat source [19],[20],[21]. Moreover, the use of natural refrigerants in heat pumps for that type of application is quite common. In fact, CO_2 working in transcritical conditions has been demonstrated as a reliable alternative with high COP [20],[21]. In addition others alternatives like propane has demonstrated high levels of performance in this type of applications [22],[23], [24].

Thermodynamically, it is well known that the substitution of the gas boiler by a heat pump is an efficient solution and has the potential of reusing some sources of waste heat. However, up to the knowledge of the authors no public research has been done related to the optimal heat pump size based on the SHW demand and on the waste heat considering, in addition, the economic part which is determinant in the final optimal solution.

In this paper, the optimal substitution of a gas boiler by a heat pump and a recovery heat exchanger (HPR) to produce SHW is analyzed. The study assumes a sanitary hot water demand always larger than the capacity of the HPR, a constant availability and temperature of waste heat that could come from sewage water or a condensation loop. Based on those two conditions, the optimal size of the components that maximize the economic benefit has been analyzed.

The paper is organized as follows: first, a description of the model is presented. Second, the performed analysis section collects the characteristics of the base case study and a sensitivity analysis description. Third, all the results obtained from the model are presented. Finally, the conclusions are discussed.

2.-DESCRIPTION OF THE MODEL

2.1. Description of the system

Figure 1 represents the basic scheme of the water to water heat pump system alone (HPA). Based on the present application, an additional recovery heat exchanger (HPR) in order to pre-heat the water before the inlet of the condenser has been also analyzed (see Figure 2).

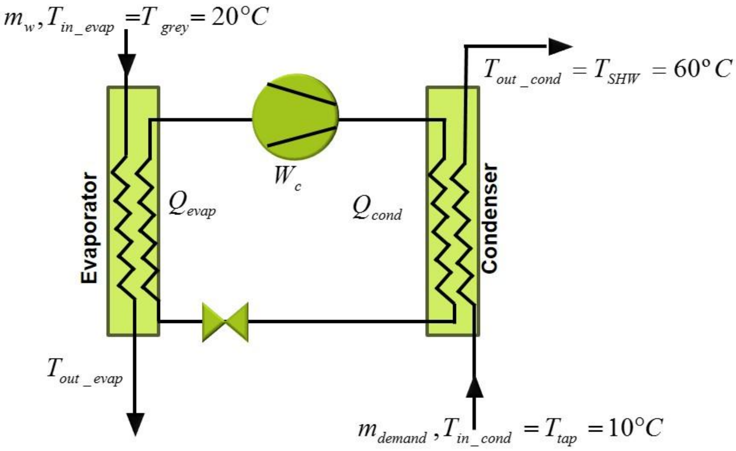

Figure 1: Heat pump alone (HPA) system layout.

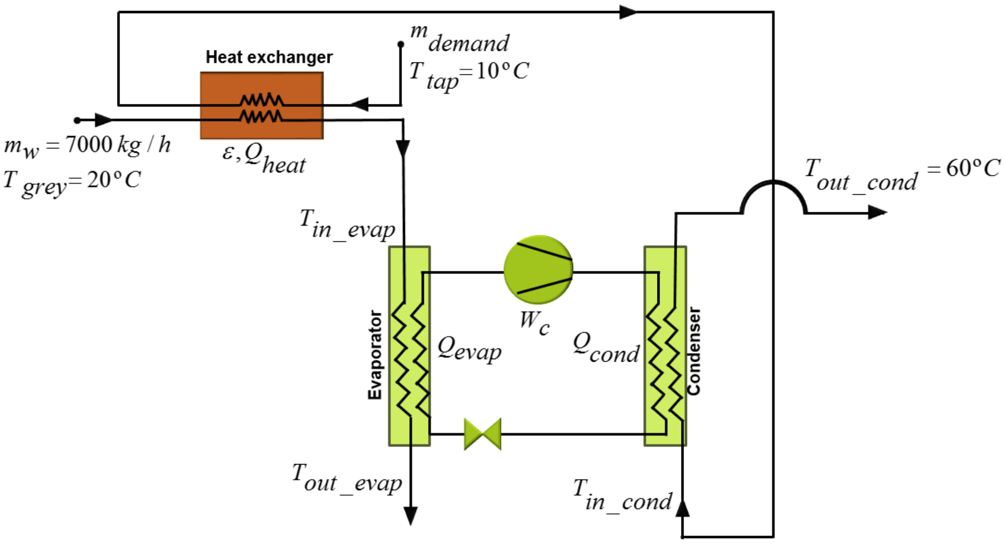

Figure 2: System layout of the heat pump with an additional recovery heat exchanger (HPR)

Characteristics of the heat pump and boundary conditions:

- The system is based on an existing prototype of a new water to water heat pump that is able to work with subcritical conditions and high COPs thanks to the sub-cooling maximization which is adapted based on the operating conditions. Further information as well as a more detailed explanation regarding to the heat pump can be found in

[22].

- The nominal heating capacity under the assumptions considered for this study is $Q_{cond} = 42.631 kW$ which is the size of the existing prototype used for the experimental results and the model validation. In the rest of the document, this value is used as the reference size.
- Refrigerant: the heat pump uses propane not only because of environmentally reasons but also due to interesting thermodynamic characteristics for this application [22], [24].
- Heat source: any available wasted source of energy at low temperature, for instance, sewage water or water from a condensing loop. In this case, water at 20°C and a constant available water mass flow rate of 7000kg h^{-1} has been considered for the base case.
- Sanitary Hot Water production: the SHW demand is assumed to be significantly higher than the production of the heat pump. The tap/fresh water is considered to be at 10°C and it will be heated until 60°C. These are, therefore, the temperature conditions of the condenser.

Characteristics of the recovery plate heat exchanger:

A preliminary study in order to choose a heat exchanger size was done based on the open access Sweep software [25] .

The heat exchanger was chosen with the following boundary conditions based on specifications from the manufacturer:

- Minimum number of plates due to efficient design: 10
- Maximum number of plates due to efficient design: 140

2.2. Model equations

2.2.1. Thermodynamic problem

First, the equations used for the recovery heat exchanger modeling are presented, second, the equations of the heat pump are exposed and third, a description of the model equations of the complete system is done.

The recovery heat exchanger modifies the water temperature at the inlet of the evaporator and condenser of the heat pump. Its influence on the heat pump performance has been evaluated modelling it by the following equations.

The heat rejected from the wastewater is calculated according Eq.1:

$$Q_{heat} = \varepsilon \cdot mcp_{\min} \cdot (T_{grey} - T_{tap}) \tag{1}$$

Where the effectivity has been modeled based on Sweep software[25]. According to that, an expression for the effectivity and the effective capacity as a function of the number of plates and the mass flow rate has been obtained:

$$\varepsilon = f(m_{demand}, Plates) \tag{2}$$

And $mcp_{\min} = \min(m_{demand} \cdot cp_w, m_w \cdot cp_w)$.

The new inlet temperatures are calculated according Eqs.3 and 4:

$$T_{in\_evap} = T_{grey} - \left(\frac{Q_{heat}}{m_w cp_w}\right) \tag{3}$$

$$T_{in\_cond} = T_{tap} - \left(\frac{Q_{heat}}{m_{demand} cp_w}\right) \tag{4}$$

Where T_{in_evap} the evaporator inlet temperature [K] and T_{in_cond} is the condenser inlet temperature [K].

The pressure drop has been calculated following the same methodology described previously for the heat transfer problem and it is shown in Eq. 5 and 6.

$$DP_{demand} = f(m_{demand}, Plates) \tag{5}$$

$$DP_{water} = f(m_w, Plates) \tag{6}$$

The heat pump model is based on empirical correlations for the COP and heating capacity developed from experimental results according to [22] as a function of the water temperature at the inlet of the condenser and the evaporating temperature including the auxiliaries. Eq. 7 and Eq. 8 show the fitting used in the model for an outlet condenser water temperature of 60°C:

$$COP_{hp} = -94.5966685 + 0.22736625 \cdot T_{in\_cond} + 0.39666425 \cdot T_{evap} - 0.00095157 \cdot T_{in\_cond} \cdot T_{evap} \tag{7}$$

$$\begin{aligned} T_{evap} = (&-201.603822 - 17.3859437 \cdot T_{in\_evap} + 19.9534897 \cdot T_{out\_evap} - 0.13609611 \cdot T^2_{in\_evap} - \\ &- 0.20473267 \cdot T^2_{out\_evap} + 0.33769076 \cdot T_{in\_evap} \cdot T_{out\_evap}) \end{aligned} \tag{8}$$

$$Q_{cond} = -837.342696 + 1.79739626 \cdot T_{in\_cond} + 3.38242539 \cdot T_{evap} - 0.00725288 \cdot T_{in\_cond} \cdot T_{evap} \tag{9}$$

Where COP_{hp} is the Coefficient of Performance, T_{evap} the evaporating temperature [K], T_{out_evap} [K], the evaporator outlet temperature and Q_{cond} the heating capacity [W].

The water mass flow rate supplied at 60°C (SHW production) is calculated from heat transfer balance according to Eq. 10.

$$m_{demand} = \frac{Q_{cond}}{cp_w (T_{out\_cond} - T_{in\_cond})} \tag{10}$$

The cooling capacity is obtained according Eq. 11:

$$Q_{evap} = Q_{cond} \frac{COP_{hp} - 1}{COP_{hp}} \tag{11}$$

Where Q_{cond} is calculated in Eq.9 and the COPhp from Eq.7.

The compressor capacity is, directly related to the heating capacity and the coefficient of performance according to Eq. 12.

$$W_c = \frac{Q_{cond}}{COP_{hp}} \tag{12}$$

The evaporator outlet water temperature is calculated using Eq.13.

$$Q_{evap} = \dot{m}_w \cdot cp_w \cdot (T_{in\_evap} - T_{out\_evap}) \tag{13}$$

The water pressure drop in the evaporator and the condenser has been calculated based on correlations obtained from experimental results.

The evaporator water pressure drop correlation is shown in the Eq. 14 and Eq. 15

$$DP_{evap} = 2 \cdot 10^{-6} \cdot m_w^2 + 4.1 \cdot 10^{-3} \cdot m_w + 19.962 \tag{14}$$

$$DP_{cond} = 1 \cdot 10^{-5} \cdot m_{demand}^2 + 2.9 \cdot 10^{-3} \cdot m_{demand} + 32.149 \tag{15}$$

Finally, the whole system (Fig. 2) has been defined as a function of COP and the heating capacity by coupling both, the heat exchanger and heat pump. These variables are defined as:

-**COP**:

The auxiliary pump consumption due to the water drop pressures (for both mass flows in the heat exchanger, the evaporator and the condenser) is calculated based on Eq. 16 according to the European standard 14511-3.

$$Power\_pump = \sum \frac{m_k \cdot DP_i}{\eta_{pump} \cdot \rho_w} \tag{16}$$

Where i =[pump_cond, pump_evap, pump_demand, pump_water], $\rho_w = 1000 kgm^{-3}$ the water density , $\eta_{pump} = 0.3$ the pump efficiency and $k = [demand, water]$ respectively.

Therefore, the COP of the HPR system is expressed in Eq.17.

$$COP_{total} = \frac{Q_{heat} + Q_{cond} + P_{pump\_cond}}{W_c + P_{pump\_cond} + P_{pump\_evap} + P_{pump\_demand} + P_{pump\_water}} \tag{17}$$

-**Total Heating Capacit**y:

The total heating capacity supplied by the HPR system is given by Eq.18

$$Q_{HPR} = Q_{heat} + Q_{cond} + DP_{pump\_cond} \tag{18}$$

Thus, the equivalent capacity supplied by the previous gas boiler -the capacity substituted by the heat pump- is calculated according to the European standard 14511-3 expressed in Eq.19

$$Q_f = \frac{Q_{cond} + Q_{heat} + P_{pump\_cond}}{\eta_{cald}} \tag{19}$$

Where $\eta_{cald} = 0.95$ is the considered boiler efficiency.

2.2.2. Economic problem

In order to evaluate the economic benefit, the approach followed in [28] has been used as a reference .

The annual benefit is calculated by the difference between saving and cost according to Eq. 20 considering the annual Saving and the equivalent annual Cost.

$$Benefit = Saving - Cost \qquad (20)$$

The cost of an inversion can be divided into three different categories: initial cost, annual cost and operating cost.

- *Initial cost:* includes the investment cost. In the present study, this cost is the heat pump price (function of its size) and the heat exchanger cost (function of the number of plates). Notice that the gas-boiler investment cost will not be considered since the assumption is that there is already gas-boilers operating to warm up the sanitary water and the study only considers the interest of substituting this production by recovering wasted heat through a heat pump.

  To calculate the yearly benefit, the equivalent annual cost must be calculated. This term can be understood as if the capital would come from a bank loan under an interest rate, *i,* to be paid off (recovered) in *n* annual payments (years). This is the term considered in "Cost" within the Eq.20.
- *Annual cost:* includes expenses derived from taxes and maintenance. In this work, the same tax rate will be applied annually for the whole scope as well as a fix an annual maintenance cost applies to the heat pump, boiler and the heat exchanger, respectively.
- *Operating cost:* costs derived from the use of the technology. The electricity price in the case of the heat pump and the Natural Gas price in the gas boiler. These prices are based on the tariffs from the company called "Gas Natural Fenosa" at date of 07/06/2016 [27].

  Electric price

  The price of the chosen Tariff 3.0A which includes an installed power greater than 15kW and a voltage <1kV with 3-periods distinction is expressed in Table 1.

Table 1: Electric tariff

Period	c€/kWh	%of time/day
1	15.5774	42
2	13.0775	33
3	9.5653	25

Another decisive parameter is the time, *t, in which the system has waste heat available and when the system is running.* The study has been done assuming it equal to 8.760h, considering that the wastewater mass flow rate is constant and available during all the hours of the year. The installation is running 24h every day. Hence, a weighted average price of the electricity is considered equals to $C_{elec\_energ} = 0.13249 eurkWh^{-1}$.

Natural gas price.

The price of the chosen Tariff 3.4. which includes yearly consumption higher than 100MWh is $C_{\_fuel} = 0.04239 eurkWh^{-1}$.

Finally, the term "Saving" includes the annual saving due to the sanitary water production using the heat pump system instead of the gas boiler. It is characterized by the difference between the operating cost of the gas-boiler and of the heat pump system. That is, the cost of the SHW production using a gas boiler for the considered size (natural gas cost and maintenance), the cost of the same production using a heat pump (electric cost and maintenance) and the maintenance cost of the heat exchanger according to Eq. 21.

$$Saving = C_{y\_op\_bo} - C_{y\_op\_HP} - C_{y\_op\_heat} \tag{21}$$

2.2.3. System maximization equation

Once the installation has been characterized, the model optimizes the size of the components based on the maximization of the term "Benefit" presented in the economic part of the modeling in Eq. 20 where the term "Saving" considers the operating costs and the term "Cost" the equivalent annual cost due to the heat pump and the heat exchanger investment cost.

The size of the heat pump and the heat exchanger to obtain the maximum benefit is obtained according to Eq.22.

$$(size, Plates) = f(\max Benefit) \tag{22}$$

Finally, the payback period is calculated as in Eq.23. This term aims to give an overall view of the required number of years to pay the total investment cost (not only under an annual point of view) for the considered life-time of the system and the correspondent originated savings. Notice that this calculation does not include the actualization of the money but it is a ratio whose components have been previously actualized following the methodology stated in [26].

$$payback(years) = Investment\_\cos t / Saving \tag{23}$$

Where the term Saving is calculated from Eq.21 and the term Investment cost includes the total investment costs (including taxes).

3. PERFORMED ANALYSIS

The main assumptions performed in the model are summarized in Table 2.

Table 2: Constant parameters in the present work

Wastewater temperature	20°C
Fresh/tap water temperature	10°C
Sanitary hot water demand temperature	60°C
Annual interest rate	3%
Number of plates	10 ≤ Plates ≤ 140
Maintenance gas boiler cost	100 €/year
Maint. Heat pump + heat exchanger cost	150 €/year

The study begins with the analysis of a reference heat available to recover which is calculated according to Eq. 24.

$$Q_{ref} = \dot{m}_w \cdot cp_w \cdot (T_{grey} - T_{out\_evap}) \tag{24}$$

Where $T_{grey} = 20^{o}C$ and $T_{out\_evap} = 0^{o}C$ (assumed to be the minimum possible temperature at the outlet of the evaporator in order to avoid the water freezing).

Afterwards, a parametric study including values of heat recovered from 5% to 85% of the heat reference has been done. Finally, the sizing of the system is defined by the percentage of heat recovered that leads to the maximum benefit. For that percentage, the size of the components (condenser and heat exchanger) is obtained through the sequence stated in Figure 3.

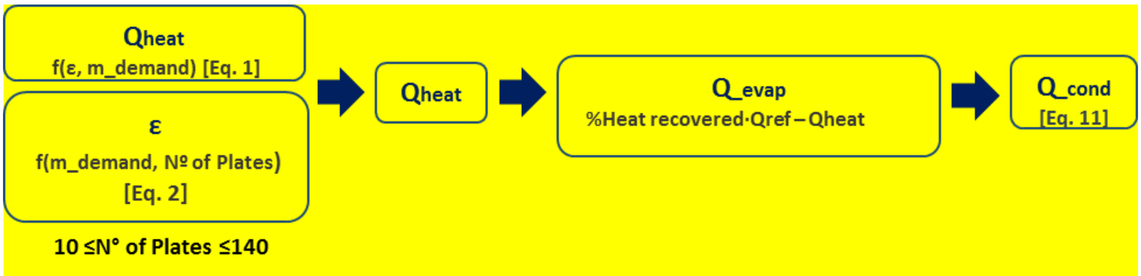

Figure 3: Followed sequence in order to size the system (heat exchanger and heat pump)

In order to dimensionless the problem, the ratio Y=Benefit [eur]/Qreference [kW] has been used in the analysis.

The work is based on a "base case" and its completed with a sensitivity study varying some of the assumptions in order to evaluate different scenarios. The following paragraphs describe the sensitivity cases and the collection of all of them, including the base case, are summarized in Table 4.

- SENSITIVITY ON THE RUNNING HOURS

The different set of variations are the running hours. The Base Case assumes that the installation has a wastewater mass flow of 7000kgs^{-1} at 20°C and a sanitary water consumption greater than the produced by the heat pump during all the hours within a year (24h/day). The second case considers the installation to be working only 12h/day, which is 4380h/year. The third case is based on 8h/day working pattern, 2920h/years and the forth case considers the operation of the installation just 4h/day, a total of 1460h/year.

This sensitivity has been kept for the other parameters variations.

- SENSITIVITY ON THE NUMBER OF PAY-OFF YEARS

The base case study has evaluated the results for 15 years of investment or heat pump life-time since any value is expected afterwards. This parameter conditions the final decision. Therefore, a heat pump life-time of 10 years has also been analyzed.

- SENSITIVITY ON THE ENERGY PRICES

The profitability and attractiveness of this investment, strongly depend on the energy prices. In the base case, the current electric and gas prices have been considered. However, the evaluation of the maximum benefit with higher electricity prices and lower gas prices is interesting.

- Electric price variation: the number “1” means the value considered in the base case. An increase of the tariff price equals to the current peak price has been considered. This is, an increase of 14%.
- Natural Gas price variation: the number “1” means the value considered in the base case. A decrease of the tariff price equals to 4% has been considered. This value is based on the IDAE statistics trend for the past 4 years[28]. In addition, a decrease on the price equals to 14% in order to compare with the electric price variation has been considered.

The sensitivity studies in this section are based on applying a pessimist view regarding to the attractiveness of the heat pump investment. Therefore, only an increase of the electric tariffs and a decrease on the gas prices has been done.

- SENSITIVITY ON THE INVESTMENT COST CONSIDERING DIFFERENT RUNNING HOURS

Finally, the last variable estimated in the study has been the cost of the heat pump and the heat exchanger. The values in the base case are based on a current manufacturer catalogue according to Eq. 26 and 27 named as “1” in the table). The sensitivity is considered as an increase of the 50% in the investment cost (cases 21-24) and a decrease of 50% (cases 25-28).

SENSITIVITY ON THE AVAILABLE SEWAGE WATER MASS FLOW

In the base case, a costant total sewage water mass flow rate of 7000kg/h has been considered through the considered number of operating hours. Different water mass flow rates available would lead to different final benefits but similar sizes at the maximum benefit. In order to demonstrate this approach, the analysis of the system with a sewage water mass flow rate of 14000kg/h and 3500kg/h has been included within this work.

4.-RESULTS AND DISCUSSION

4.1. Study of a heat pump vs system heat exchanger-heat pump

First, an evaluation of the ratio ʒ for the HPA considering the nominal heating capacity and the base case assumptions has been done. The first column of Table 3 collects the results of the maximum benefit case.

Second, the evaluation of the HPR has been performed. Considering the same heat pump size used in the previous case, the evaluation of the profitability by the addition of a heat exchanger based on its size has been performed. This is, the optimization of its area in order to maximize the benefit. The second column of Table 3 contains the results of this case.

Figura 3a represents the evolution of the COP_{hp} and the COP_total with the increase of the heat exchanger area (by means of the increase of the number of plates) adapting to the maximum possible subcooling for every condition. As it can be seen, the COP_{hp} decreases with the increase of the heat exchanger size. The bigger the heat exchange is, the smaller the capacity of the heat pump is.

Figure 3b shows the annual Benefit, the Cost and the Saving according to Eq. 22 and 23 versus the increase of the heat exchanger area. The grey line represents the benefit of the case considering only the heat pump (HPA).

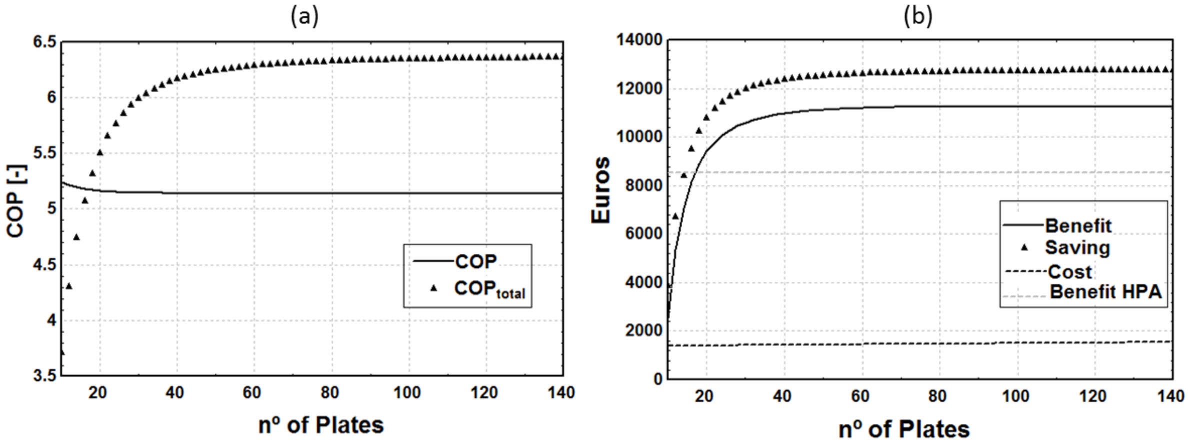

Figure 3: (a) Variation of the COPhp (HPA) and the COP_total (HPR) with the n° of plates of the heat exchanger (b) Variation of the Benefit, Saving and Cost of the system with the n° of plates of the heat exchanger

From (a) and (b) can be inferred that COP_total and the Benefit increases significantly until the effectivity of the heat exchanger becomes almost one (around 80 plates). In this case, the maximum Benefit occurs when using a heat exchanger of 100 plates and it equals to 11,266€ (annually).

The influence of the number of plates in the investment cost is low because it is divided by the number of operation years considered (15years). As in Figure 3 this influence cannot be clearly appreciated due to the scale, Figure 4 represents only the term “Cost” with the addition of number of plates and it increases from 1400eur/years to 1550 eur/years. This term is an annual term that considers the investment cost, the maintenance cost and the operating cost.

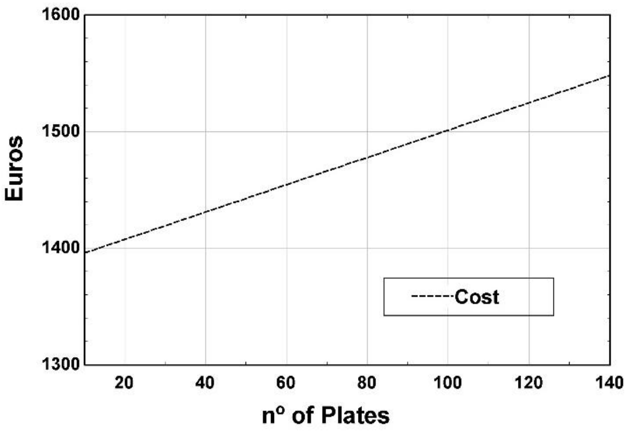

Figure 4: Cost evolution for a heat pump size of one and the variation of the number of plates of the recovery heat exchanger.

Table 3 collects the main thermos and economic parameters for the optimal case.

Table 3. Output of the system (heat pump + heat exchanger) case

	Heat pump	Heat pump + Heat exchanger
Q ref (kW)	162.556	162.556
% of heat recovered	23.45 %	27.53 %
THERMODYNAMIC VARIABLES		
Tin_cond (°C)	10	19.81
Tout_cond (°C)	60	60
Tin_evap (°C)	20	18.72
Tout_evap (°C)	15.31	14.49
Q_cond (kW)	42.63	42.63
Wc (kW)	8.2	8.2
Q_heat (kW)	-	10.41
COP_{hp}	5.66	5.142
COP_total	5.649	6.356
mw (kg/h)	7000	7000
m_demand (kgh^{-1})	798	913.68
ECONOMIC RESULTS		
Annual equivalent cost (€)	1351	1501
Annual saving (€)	9973	12767
Annual benefit (€)	8622	11266
Y (€/kW)	53.04	69.3
Payback (years)	1.62	1.37

From Table 3 can be said that the substitution of the SHW production from a gas boiler to a heat pump is very profitable. The annual benefit is 8622€ with a COP_total, of 5.649. This means that, asking for a bank loan with 3% of interest the investment cost on a heat pump, the payoff to the bank would be 1351€ annually during 15 years while you will be saving 9973€, leading to a benefit of 8622€ during the considered life-time.

The investment on the system composed by the heat pump and the heat exchanger (HPR) brings considerably more profitability than the heat pump itself. Specifically, the benefit for the best case is 23.4% higher. The benefit of the HPR is higher than the benefit of the HPA when the number of plates is greater than 18, even if it is not the optimum.

Based on these results, the HPR has demonstrated a greater performance than the HPA. Therefore, now the size of the heat pump as well as the recovery heat exchanger are studied in order to be optimized.

4.2. Study of the optimal size of HPR to maximize the Benefit.

The analyisis of each case consists of:

- Evaluation of the COP_total
- Estimation of the Benefit
- Optimal size that maximizes the benefit

4.2.1. Base Case

Figure 5a represents the COP_hp as a function of the percentage of energy recovered and the number of plates. Grey color corresponds to the highest value and it is found with low values of number of plates in the heat exchanger and relatively low percentages of heat recovered. This result can be related to the size of the heat pump. Moreover, the variation has more influence in the COP than in the number of plates. The maximum COP_hp (5.3) is found for values of heat recovered around 15% which means heating capacities around 25kW and only 20 plates considering HPR. Nevertheless, it is worthy to notice that the maximum COP_hp is 5.767 and it occurs for the HPA of the same size as the considered in the system.

Figure 5b represents the COP_total as a function of the percentage of energy recovered and the number of plates. Grey color corresponds to the highest value. The COP_total increases as the percentage of heat recovered decreases and with the addition of plates (higher UA values). It should be noticed that the optimal number of plates depends on the heat exchanger effectivity and hence, the trend is not linear. The maximum values correspond to large heat exchangers and relatively small heat pump sizes. Thermodynamically, this can be explained as the COP_total takes into account both components of the system, the heat exchanger (which exchanged heat is given “for free”) and the heat pump. The maximum COP_total is around 6.51 and occurs for the maximum heat exchanger size and the most efficient (in terms of COP) heat pump which, according to figure 5a, corresponds to a heating capacity around 25kW.

Figure 5c represents the ratio Y[€/kW] = Benefit/Qref as a function of the percentage of heat recovered and the number of plates. Grey color corresponds to the highest benefit. The maximum values of Y occur when the percentage of heat recovered is located around 50% and increases with the addition of plates to the heat exchanger until around 80 number of plates from when the ratio becomes very similar according to the effectivity of the heat exchanger curve. It is noticeable that maximum benefit ratio (Y >100€/kW) does not correspond to the maximum COP_ total, this fact means that other considerations like the investment cost and the energy produced with it, among others, must be considered in order to determinate the most profitable solution. In this case, the increase of the HPR capacity leads to higher operational savings despite of the increment of the investment.

From figure 5c it can be extracted that values of 103€/year per kW of heat recovered by the substitution of a gas boiler by a heat pump of 82.45kW and a heat exchanger of 19.6kW can be obtained.

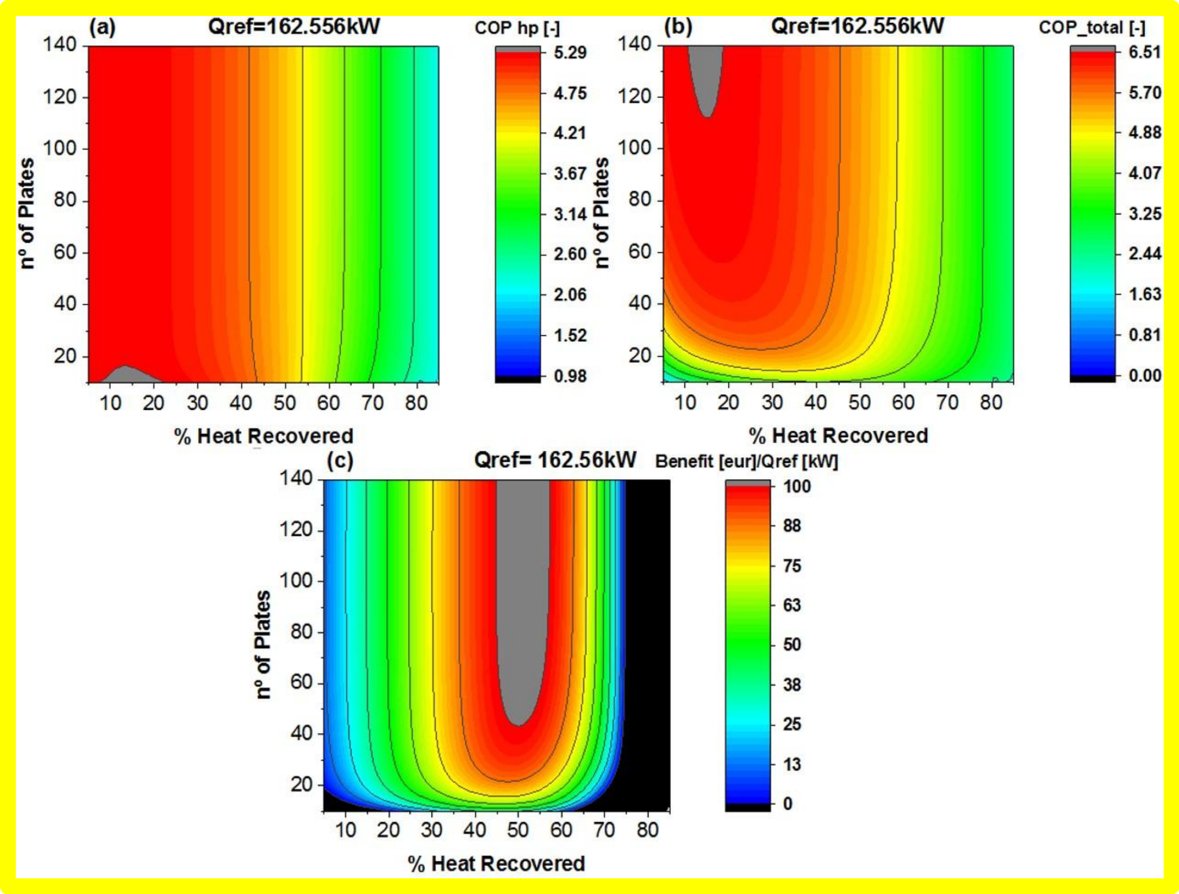

Figure 5: (a) COP variation function of the percentage of heat recovered and number of plates. Base case. (b) COP_total variation function of the percentage of heat recovered and number of plates. Base case. (c). Y=Benefit/Qref variation function of the percentage of heat recovered and number of plates. Base case.

Figure 6a presents the variation of the ratio annual investment cost of the HPR/Qref as a function of the heat pump and the percentage of heat recovered. The term annual investment cost is the total investment cost in yearly values including the annual interest rate. As it can be observed, the investment cost increases with the percentage of heat recovered (bigger HPA) and with the number of plates. The heat exchanger investment cost, has major contribution as the heat pump is smaller. The total investment cost increases with the number of plates proportionally much more for values of heating recovered lower than 40% than for higher recovered values where the increase of the size in the heat exchanger becomes much less important in the total investment cost.

Figure 6b presents the variation of the ratio saving/Qref as a function of the heat pump and the percentage of heat recovered. The saving includes the operating costs of both, the HPR and the gas boiler. Similar trend as in Figure 5c for the benefit can be observed. As the percentage of heat recovered increases the saving term rises until a maximum which corresponds to a values around 55% of heat recovered and saving rate of more than 125€/kW recovered. With the increase of the HPR size, the COP_total decreases (Figure 5b) and the consumption of the compressor with the auxiliaries increases, reaching values of the saving that can be even negative.

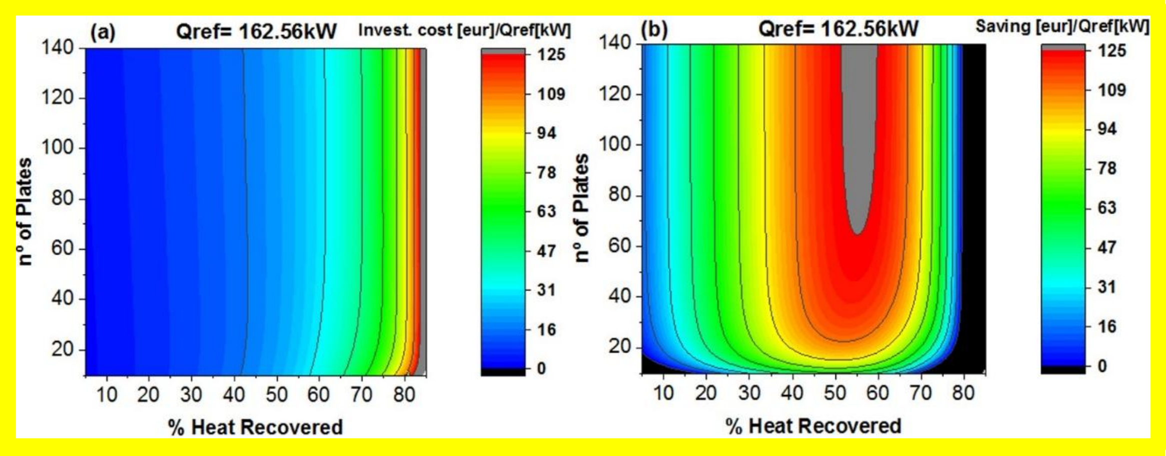

Figure 6: (a)Annual investment cost of the system/Qref function of the percentage of heat recovered and the number of plates for the base case. (b) Saving/Qref of the system function of the percentage of heat recovered and the number of plates for the base case.

Figure 7 represents the variation of the ratio heating capacity/Qref with the number of plates and the percentage of heat recovered. This figure allows to have an idea about the sizes of the heat pump for the base case. As it can be seen in the figure, the size of the HPA increases as the percentage of heat recovered increases. Regarding to the number of plates, the size of the HPA depends on the effectivity of the heat exchanger curve: being needed for the same percentage of heat recovered a larger HPA when the number of plates is low (small HE) and remaining practically constant once the effectivity achieves values close to one (from 80 plates). This effect is more important as the size of the HPA increases.

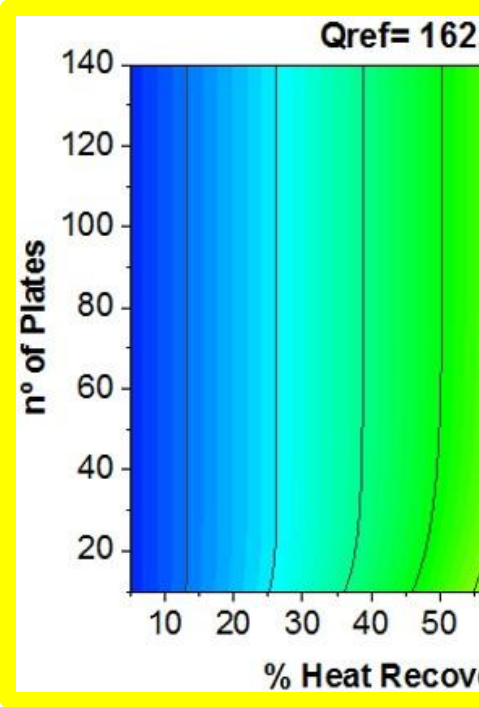

Figure 7: Heat pump size/Qref function of the percentage of heat recovered and the number of plates for the base case.

4.2.2. Cases 1-4

These cases represent the study of the operating hours influence on the final benefit. The reference heat for the cases 1-27 is 162.56kW which corresponds to an available water mass flow rate from the sewage of 7000kg/h. Figure 8 shows the variation of the ratio Y[€/kW] = Benefit/Qref with the percentage of heat recovered and number of plates of the heat exchanger for different available operating hours. Grey color corresponds to the highest benefit and black color to negative values of the benefit.

According to the figure, as the operating time is larger, the optimal size of the heat exchanger and the heat pump size increase and the annual benefit is higher. Nevertheless, in terms of percentage of heat recovered, values around 50% lead to the best solution from a certain number of operating hours. The annual investment cost becomes more important as the number operating hour decreases. The same investment size could lead to a benefit (>16000eur) if the installation is used 24h/days (51% of heat recovered) or could lead to a not profitable investment (negative benefit) for example if the installation is used only 4h/day. Therefore, the effect of the operating hours is determinant. Thus, a critical variable when trying to find the optimal size of these systems is the availability and the use that the system will have.

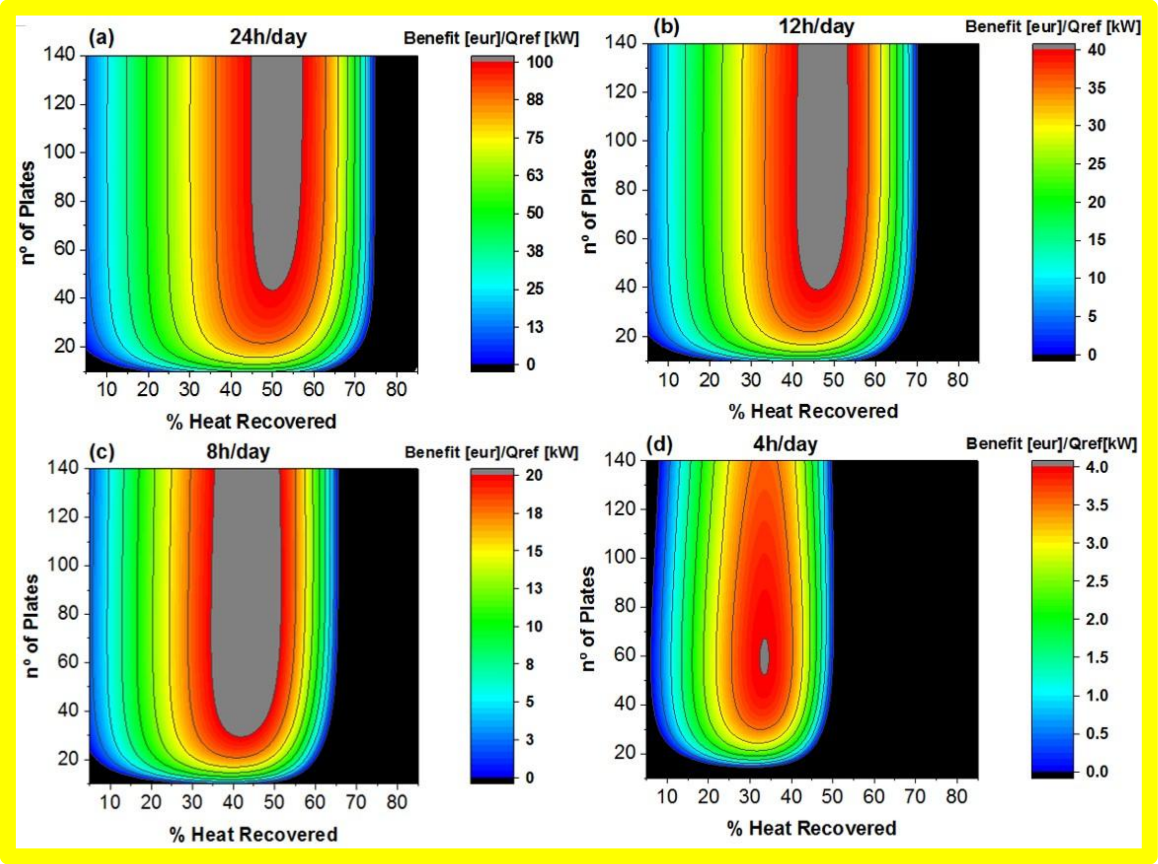

Figure 8: Y=Benefit/Qref variation function of the percentage of heat recovered and number of plates. (a) Base case (24h/day); (b) 12h/day; (c) 8h/day; (d) 4h/day. The colors of the scale have not been maintained across the graphs due to scale differences.

It should be noticed that the COP_total increases with the diminution of the HPA size. However, based on the electricity and gas price assumptions, the influence of the production volume on the annual benefit becomes more important as the size increases. While the benefit from using the installation 24h/day to the lowest use (4h/day) is reduced around 96%, the SHW production capacity reduces 37%.

Table 5 collects the main thermodynamic, economic and the optimal sizes of the maximum benefit for all the cases.

4.2.3. Cases 5-28

The rest of the sensitivity study is presented only for the optimal solution in order to be able to have an overall view of the results summarized in Table 5.

Figure 9 represents the maximum ratio Y=Benefit/Qref in monetary terms for each case. The horizontal lines are the maximum benefits for the operating hours considered in the base case.

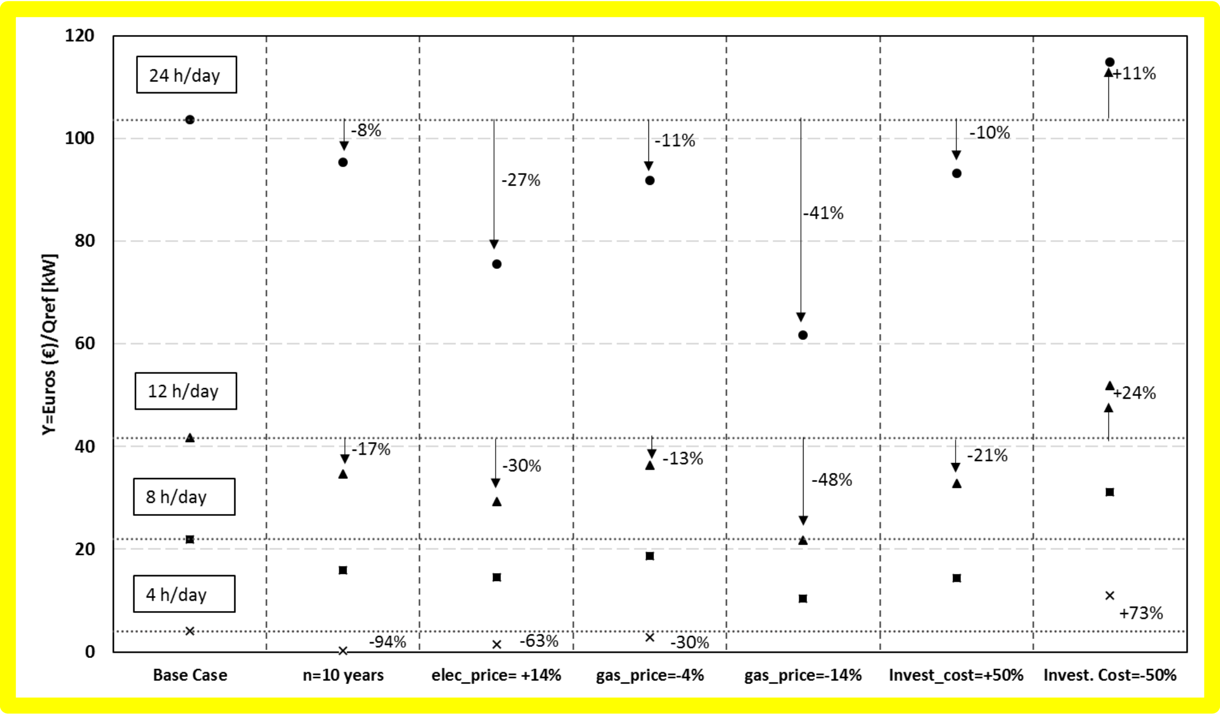

Figure 9: Maximum ratio Benefit/Qref of any studied case based on the number of operating hours.

The 14% decrease on the gas price is the most influent parameter followed by the increase on the electricity price as well as the decrease of 4% on the gas price, except for low operation hours represented by last series (4h/day). Therefore, in general, the most influent effect on the maximum benefit is the electricity/gas price. Their volatility as well as the dependency on external factors make the investment decision riskier. However, from a determined number of operating hours, all the cases experiment high benefits by the substitution of the SHW production from a gas boiler to a heat pump.

Regarding to the investment cost influence and considering that the cost of the heat pump and the heat exchanger were conservative in the base case, even increasing it by 50%, the investment would still be profitable.

According to the followed approach, the investment cost is divided by “annual equivalent” quantities as if a loan were asked to the bank. The time in which this “loan” must be returned as well as the interest rate of it is also an important variable. In this study, a 3% of interest rate has been considered (pessimistic rate with the current bank situation) a 15 years’ period (also pessimistic due to the heat pump lifetime is expected to be higher than 15). Nevertheless, even if the study is made for 10 years of lifetime, the investment reminds highly beneficial.

Figure 10a represents the optimal heat pump size (heating capacity kW) for each case and operating hours.

The more operating hours, the higher savings and benefits. Thus, bigger sizes of the heat pump (it is shown by the upper dots).

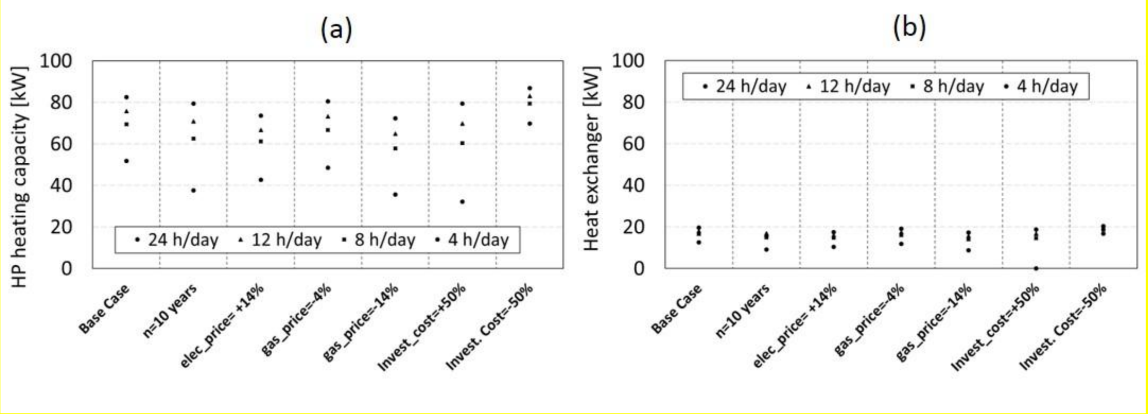

Figure 10: (a) Optimal heat pump heating capacity of every considered case (b) Optimal heat exchanger capacity for every considered case.

The optimal size of the heat pump strongly depends on external variables like the grey water temperature, the gas and electric price, the investment cost and the like. Nevertheless, if the operating hours is greater than 4.1h/day, the substitution of a gas boiler by a heat pump is profitable even under a wide range of conservative conditions according to the results of this study.

Figure 10b represents the optimal number of plates of the recovery heat exchanger for each case. The optimal number of plates of the heat exchanger is mainly influenced by the investment cost and the use of the installation. In any case, the maximum benefit occurs with a medium/high number of plates which result for the considered heat exchanger of capacities around 18kW for most of the considered cases.

It should be noticed that the optimum recovery heat exchanger depends mainly on the operation hours. Hence, defined this parameter, a good estimation of the optimal size can be done.

Finally, Figure 11 represents the payback period of the optimal investment for the considered life-time (15 years except for the case that is 10 years).

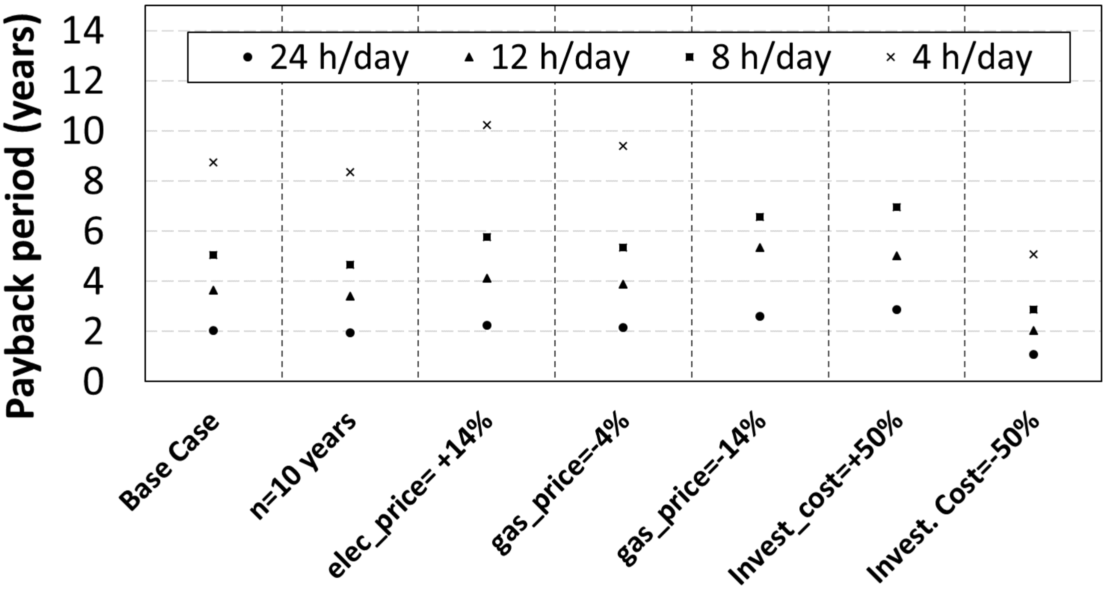

Figure 11: Payback time for every considered case

As it can be seen from the figure, the payback period depends on the number of life-time considered for the system and indirectly on the number of operating hours. However, the frame of the payback time is narrow (from a considerable number of operating hours, the expected payback time varies from 2-6 years).

4.2.4. Cases 29-30

The last sensitivity case is the study of the influence of the available water mass flow rate (sewage mass flow rate) in the most profitable solution. Two more available mass flow rates have been considered within this cases: half of the base case water mass flow rate (3500kg/h) and double (14000kg/h).

Figure 12 represents the rate Benefit/Qref obtained for (a) 3500kg/h and (b) 14000kg/h of available sewage mass flow rate function of the percentage of heat recovered and the number of plates.

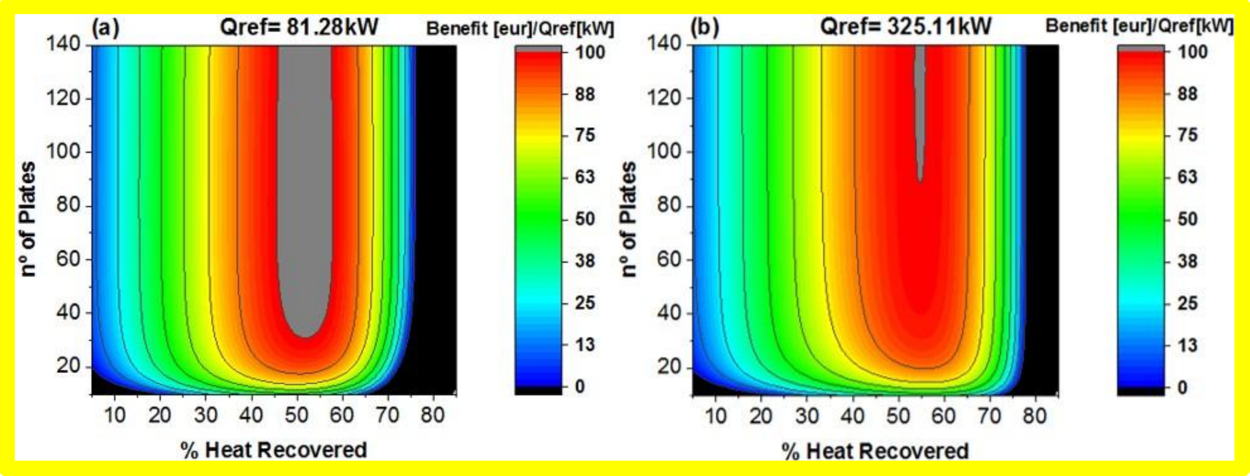

Figure 12: Ratio Benefit/Qref variation function of the percentage of heat recovered and number of plates. (a)mw= 3500kg/h,(b)mw=14000kg/h.

As it can be observed from Figure 12, the maximum benefit states around the same percentage of heat recovered (50-55%) in both cases according to what happens also for the base case (8760kg/h) in Figure 5c. Therefore, the heat available influences the final annual benefit obtained but not the ratio (which is very similar in the three cases) and not the maximum value (which is located for very similar percentages of heat recovered). The number of plates that lead to that maximum benefit states around 80 for the three cases. In addition, the variation of the benefit across the number of plates for the respective percentage of heat recovered has a very flat slope, not penalizing very much in the final benefit. This can be seen for the base case in Figure 13.

Figure 13 represents the variation of the benefit with the number of plates for the base case and the percentage of heat recovered of 51.06% which corresponds to the highest benefit.

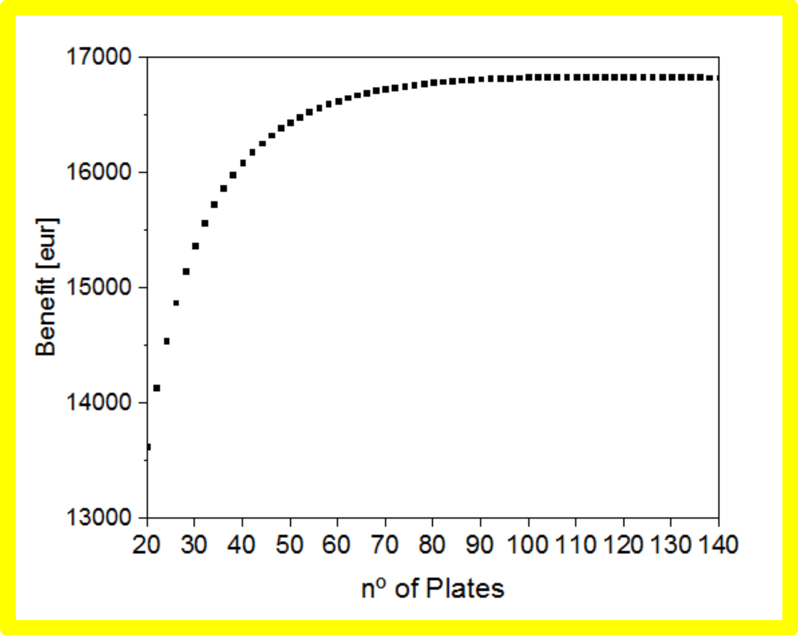

Figure 13: Benefit variation with the number of plates for the base case and 51.06% of recovered heat.

5.- CONCLUSION

In this work, an analysis of the potential profitability derived from the substitution of the SHW production from a conventional technology (gas boiler) to a new heat pump booster to recover heat from a low temperature water source has been done.

This analysis consists of an optimization of the heat pump size to maximize the benefit.

The main conclusions of this work are:

- The introduction of a recovery heat exchanger is always positive.
- As a consequence of the number of external variables required in order to find the optimal solution of this kind of system, a sensitive analysis of the influence of the different variables involved in the process has been done. From that, it has been determined that as far as the number of operating hours are greater than 1500 within a year, the investment reminds clearly profitable, even under the hypothesis of considering a 14% variation in gas/electricity prices, 50% of variation in the investment cost and a 33% of the reduction in the heat system lifetime. Therefore, the heat pump demonstrates that is a very interesting and cost effective technology for this type of applications.
- The size that corresponds to the maximum benefit of the recovery heat exchanger, the heat pump as well as the payback period depends mainly on the operating hours.
- The maximum benefit of the system strongly depends on the properly sizing of it. It is worth it to notice that the maximum benefit does not take place for a heat pump size with the highest benefit but to a size that optimizes the whole system (the heat pump and the heat exchanger) for a given external conditions.
- Results for the base case show that the substitution of the gas boiler by the heat pump can lead to annual benefits of around 103€/kW of heat recovered and this ratio remains very similar with the variation of the available water mass flow rate from the sewage to recover.

Finally, from all this work it has been proved that the system composed of a heat pump booster with a recovery heat exchanger has great potential to substitute conventional technologies as for instance boilers, to produce SHW. The accurate sizing of the system is crucial to obtain the maximum benefit.

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Table 4. Parameters variation. Base and sensitivity cases.

CASE NUMBER	MW [Kg/h]	INVESTMENT COST [€]	GAS PRICE [€/kWh]	ELECTRIC PRICE [€/kWh]	PAY-OFF YEARS [years]	RUNNING HOURS [h]
1 BASE CASE	7000	1	0.04239	0.13249	15	8760
2	1	1	1	1	15	4380
3	1	1	1	1	15	2920
4	1	1	1	1	15	1460
5	1	1	1	1	10	8760
6	1	1	1	1	10	4380
7	1	1	1	1	10	2920
8	1	1	1	1	10	1460
9	1	1	1	+14%	15	8760
10	1	1	1	+14%	15	4380
11	1	1	1	+14%	15	2920
12	1	1	1	+14%	15	1460
13	1	1	-4%	1	15	8760
14	1	1	-4%	1	15	4380
15	1	1	-4%	1	15	2920
16	1	1	-4%	1	15	1460
17	1	1	-14%	1	15	8760
18	1	1	-14%	1	15	4380
19	1	1	-14%	1	15	2920
20	1	1	-14%	1	15	1460
21	1	1.5	1	1	15	8760
22	1	1.5	1	1	15	4380
23	1	1.5	1	1	15	2920
24	1	1.5	1	1	15	1460
25	1	0.5	1	1	15	8760
26	1	0.5	1	1	15	4380
27	1	0.5	1	1	15	2920
28	1	0.5	1	1	15	1460
29	3500	1	1	1	1	1
30	14000	1	1	1	1	1

Table 5. Summary of the main results for the base and the sensitivity cases.

CASE NUMBER	Tin_cond (°C)	Tout_cond (°C)	Tin_evap (°C)	Tout_evap (°C)	Tevap (°C)	Qref (kW)	Qrecovered (%)	Q_heat (kW)	COP	COP_total	m_demand (kg/h)	Annual equivalent cost (€)	Annual saving (€)	Y(€/kW) Annual Benef/Qref	Heat pump size (kW)	Nº of plates	Payback (years)
1	19.55	60	17.59	9.721	0.99	162.56	51.06	19.6	4.34	5.35	1768.7	3459	20299	103.593	82.45	110	2.04
2	19.6	60	17.79	10.53	2.586	162.56	47.35	17.97	4.52	5.58	1613.16	2974	9751	41.695	75.76	88	3.64
3	19.64	60	17.96	11.26	3.87	162.56	43.79	16.55	4.68	5.761	1476	2608	6171	21.918	69.45	76	5.046
4	19.76	60	18.45	13.33	6.746	162.56	33.28	12.6	5.01	6.144	1112.4	1804	2456	4.012	51.87	58	8.76
5	19.57	60	17.67	10.04	1.637	162.56	49.44	15.5	4.42	5.45	1707.5	4563	20058	95.325	79.48	102	1.94
6	19.63	60	17.92	11.09	3.569	162.56	44.6	16.9	4.64	5.72	1510.92	3770	9413	34.713	70.85	80	3.417
7	19.69	60	18.16	12.11	5.181	162.56	39.75	14.93	4.83	5.94	1326.24	3142	5729	15.914	62.55	66	4.67
8	19.83	60	18.88	15.18	8.356	162.56	24.39	9.105	5.2	6.318	797.76	1758	1795	0.227	37.68	52	8.35
9	19.63	60	17.85	10.8	3.072	162.56	46.21	17.49	4.58	5.66	1563.5	15139	2864	75.511	73.65	110	2.26
10	19.67	60	18.02	11.51	4.27	162.56	42.17	15.99	4.72	5.827	1433.88	2512	7275	29.300	66.63	86	4.12
11	19.71	60	18.19	12.25	5.38	162.56	38.94	14.75	4.85	5.979	1301.4	2201	4570	14.573	61.17	74	5.75
12	19.81	60	18.72	14.49	7.863	162.56	27.63	10.41	5.14	6.297	913.68	1455	1694	1.473	42.78	60	10.25
13	19.57	60	17.65	9.99	1.544	162.56	38.29	19.074	4.40	5.433	1716.5	3297	18213	91.763	80.57	110	2.16
14	19.62	60	17.85	10.8	3.073	162.56	35.25	17.436	4.58	5.652	1563.12	2839	8738	30.173	73.30	88	3.88
15	19.67	60	18.04	11.57	4.373	162.56	32.35	15.96	4.73	5.832	1422	2471	5498	18.621	66.69	74	5.36
16	19.78	60	18.55	13.76	7.2	162.56	23.95	11.8	5.06	6.205	1038.6	1669	2122	2.789	48.52	58	9.39
17	19.64	60	17.88	10.91	3.269	162.56	45.47	17.269	4.60	5.687	1542.96	2801	12823	61.651	72.39	102	2.61
18	19.69	60	18.08	11.77	4.674	162.56	41.11	15.602	4.77	5.882	1387.08	2397	6079	22.650	64.89	80	5.35
19	19.73	60	18.28	12.61	5.878	162.56	36.95	13.98	4.91	6.049	1237	2063	3754	10.402	57.87	72	6.56
20	19.84	60	18.93	15.39	8.477	162.56	23.06	8.719	5.21	6.359	763.2	1209	1204	-0.030	35.61	58	-
21	19.58	60	10.13	10.1	1.824	162.56	49.41	18.78	4.44	5.472	1689.12	4806	19945	93.135	79.48	100	2.88
22	19.64	60	17.95	11.2	3.769	162.56	44.01	16.67	4.66	5.748	1489.32	3957	9301	32.880	69.85	78	5.01
23	19.71	60	18.21	12.32	5.482	162.56	38.38	14.52	4.86	5.98	1288.44	3243	5576	14.352	60.27	64	6.97
24	10	60	20	16.73	9.616	162.56	16.35	0	5.75	5.743	554.4	1379	1346	-0.201	32.17	0	-
25	15.52	60	17.48	9.305	0.122	162.56	53.46	20.462	4.24	5.226	1850.76	1881	20560	114.911	86.95	138	1.09
26	19.55	60	17.59	9.721	0.998	162.56	51.4	19.601	4.34	5.351	1768.7	1728	10148	51.796	83.11	108	2.03
27	19.58	60	17.69	10.13	1.824	162.56	49.35	18.78	4.43	5.472	1689.12	1602	6648	31.047	79.36	100	2.87
28	19.64	60	17.95	11.2	3.769	162.56	44.01	16.67	4.66	5.748	1489.32	1319	3100	10.962	69.85	78	5.08
29	19.82	60	17.5	9.626	0.8695	81.28	51.87	10.17	4.32	5.35	892.44	1789	10204	103.531	41.63	80	2.09
30	18.55	60	17.92	10.11	1.554	325.11	49.46	33.81	4.44	5.345	3405.96	6519	39070	100.120	163.9	126	1.99