Paper Number: 29412

Energy optimization of a thermal storage tank for Domestic Hot Water production

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ABSTRACT

According to the European Commission, the residential sector is responsible at this moment of the 40 % of the energy consumption and 36 % of the associated CO2 emissions in Europe. Regarding the water heating consumption, it is currently responsible for 14.5 % energy consumption of the average European dwelling. This percentage is expected to increase drastically within the concept of Near Zero Energy Building (NZEB) since the associated heating consumption percentage will be decreased largely. In this way, the energy consumption associated for water heating should be reduced, and it only can be done by using highly energy efficient technologies, such as heat pump (HP), and decreasing the energy losses associated to the facilities.

In the frame of the European Project NEXTHPG of the 7th framework program, a new prototype of heat pump booster for the production of domestic hot water was developed. The developed prototype uses an innovative subcooling control system, which allows increasing the COP of the system in more than 30% compared to conventional subcritical heat pump systems. Nevertheless, in a real installation apart from the heat pump there are other factors contributing to the final energy consumption of the whole system like system configuration, control algorithm, tank size and the like. Therefore, an estimation of the final energy consumption of the system could be significantly different from the obtained taking into account only the pump performance.

The present work is focused on the development of a model in order to optimize the design of the whole system using the prototype of the NEXTHPG project in order to satisfy the domestic hot water demand of a building for 20 people. The integrated system model will include the heat pump, the water tank, a heat exchanger in order to recover part of the waste heat (such as the heat coming from the sewage water in the domestic sector or from condensing loops in tertiary sector) and a random generator of domestic hot water demand profile.

From the results of this work, the proper sizing of the heat pump and the water tank, as well as the control algorithm, are obtained and the potential annual energy consumption of this type of system is estimated.

Keywords: *domestic hot water, heat pump, energy efficiency, optimization, subcooling control*

1. Introduction

At the present time, in Europe the energy consumption percentage associated to Domestic Hot Water (DHW) accounts for 14.5 %, whereas the one associated to Heating Ventilation and Air conditioning (HVAC) accounts for 65 % [1]. According to the values, the percentage associated to DHW is currently much lower than the one of HVAC. However, with the concept of Near Zero Energy Buildings (NZEB) the percentage of DHW will highly increase in the near future since the objective of the NZEB concept consists on reducing the heating demand at its maximum extent. In this way, the DHW energy consumption will play a key role in the near future regarding the objective of reducing the energy consumption of the residential sector. In order to reduce the energy consumption of the DHW it is not only the efficiency of the production system that should be optimized, with high efficiency technologies such the Heat Pump (HP) technology, but also the rest of the components of the facility with a proper design and sizing.

There are in the literature many studies dedicated to increase the energy efficiency of the HP itself such as the ones shown in [2, 3], but there is a lack of studies regarding the appropriate design and sizing of the rest of the components, such as the Thermal Energy Storage (TES) of the system, which absolutely affects the performance of the HP itself and the whole facility. There are some studies addressing the performance and optimization of the stratified tanks, such as [4], and others addressing control strategies and hydraulic integration of components, such as [5, 6]. That is why this paper address the appropriate design and sizing of the duality HP-TES system, and its influence over the global system energy efficiency. This work makes use of the innovative HP model developed under the frame of NEXTHPG European project [7].

In this way, the aim of this work is to perform the optimal design of the system taking into account not the efficiency of the HP itself but the global efficiency of the system. Thus, the objective of this work is not only to obtain the optimal value of the duality HP-TES system for the case analyzed but also to obtain the optimal TES volume for each of the HP sizes analyzed. In addition, the control of the system is going to be analyzed in this paper, and the optimal strategy concerning the system global efficiency will be obtained. The case analyzed corresponds to a DHW demand of 20 multi-family houses of 1.98 people per house and there are included some restrictions for guaranteeing always the comfort of the user regarding the availability of DHW at a certain temperature.

This document is split in four main parts: introduction, methodology, results and discussion and conclusions. In the first section, a brief summary of the issue, make the reader aware of the motivation of this topic and the objectives. In the second section the model and the process are commented. Within this section the reader can understand how the model was created in TRNSYS, the assumptions and requirements imposed for the optimization and fully understand the analysis of the results. A final section, the results and discussion, where the results are shown in graphics and tables to present it clear to the reader. Finally, the conclusions section is included where the most important results of the work are presented.

2. Methodology

An integrated system model was created using TRNSYS transient simulation tool [8]. In *Figure 1* the TRNSYS integrated system model used for the simulations is shown.

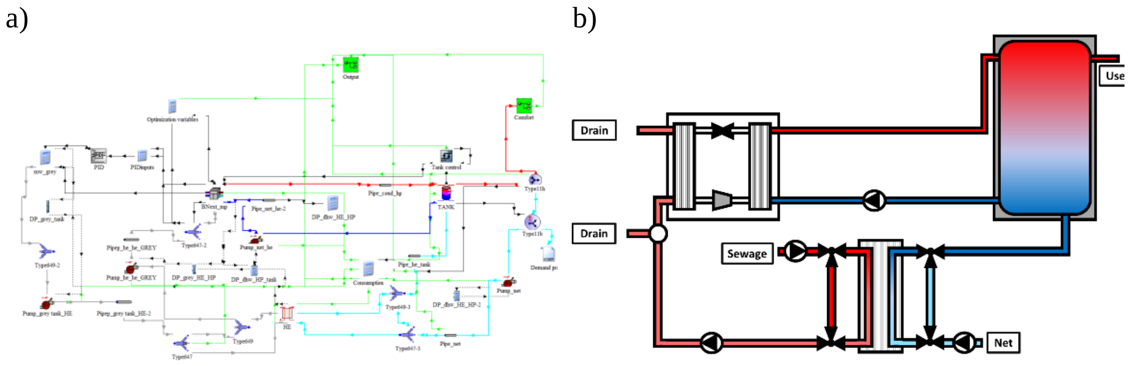

Figure 1. Illustrative description of the model: a) TRNSYS integrated system model and b) sketch of the model.

The model main components are the HP, the TES system and the heat exchanger. The HP and TES system are interconnected through a direct connection that will be deeply explained in section 2.2. Considerations and assumptions. The TES system outlet is connected to a mixer valve, since the set-point temperature in the tank is 60 ºC and the user demand temperature is 45 ºC. The water from the net is preheated in the heat exchanger before entering to the tank and the hot stream of the heat exchanger comes from the sewage water that serves as secondary fluid in the evaporator after the heat exchange process. The control consists on a hysteresis controller that commands the set point temperature in the selected node of the storage tank. Three different possibilities are analyzed: top node, second node and fifth node. The user demand corresponds to a 20 multi-family houses of 1.98 people per house and has been obtained from [9], considering one year period.

As it has been said, the HP model corresponds with the model developed in the frame of the project NEXTHPG European project [7], named as Subcooled Heat Pump (SHP). The SHP introduces an innovative type of control, through the subcooling, that allows it to work with variable temperature lift in the condenser; for more information view [10–12]. It is a 47 kW nominal capacity SHP with a nominal COP of 5.71 working with R290 (Propane) as refrigerant. The SHP has been experimentally tested and fully characterized in the laboratory and implemented in TRNSYS as a black box model by introducing the correlations obtained in a new TRNSYS type [13]. In the TRNSYS model the temperature lift in the evaporator is maintained constant at 4.5 K through a PID controller. The TES system consists on a stratified storage tank, modelled considering 15 equal volume nodes with the TRNSYS type 60. The height of the inlets and outlets are placed alike a commercial tank: inlet to the TES from the SHP at 90 % of the total height, outlet from the TES to the SHP at 10 %, outlet from the TES to the user at 95 % and finally inlet from the net at 5 %. Finally, the heat exchanger is used to preheat the cold-water inlet in the tank with the sewage water considering an unlimited availability. The heat exchanger operation is only considered when the SHP is switched on and there is DHW demand from the user. Four circulation pumps are introduced in the model, two connecting sewage-heat exchanger-evaporator, another connecting the heat exchanger with the TES system and another one connecting the TES system and the SHP condenser.

Although one model is used, the parameters referring the size of SHP and TES are changed within this evaluation. The correct selection of the node control, the point in the tank that is measured and selected as temperature set-point, has an important influence in the performance of the system. The variables used for the optimization are the scale of the SHP, this is the size of the SHP, and the volume of the tank. There is an optimum design and size for these components. The scale parameter varies from 0.1 to 1 and the volume of the tank from 0.1 to 2 m^3. The temperature set point is varied and is set in the upper node, the 1st, in the following one, the 2nd and in the 5th. The study has been performed for a year.

2.1. Performance indicators and requirements

The performance indicator chosen is the SPF$_{user}$ similar to the Seasonal performance factor (SPF) defined in "SEasonal PErformance factor and MOnitoring for heat pump systems in the building sector" (SEPEMO-Build) is a ratio that assess the energy performance of the system [14]. The SPF$_{user}$ is an own defined indicator used for the evaluation of the whole system considering the total energy provided to the user, with the water flow after the mixer valve, and the total consumption of the components included in the mode: SHP and circulation pumps. The mentioned indicator is defined as follows:

$$SPF_{user} = \frac{Q_{user}}{W_{compressor} + W_{pump1\_sewage} + W_{pump2\_sewage} + W_{pump3\_net} + W_{pump4\_HPtoTES}} \quad (1)$$

In order to guarantee the user comfort, regarding the availability of DHW at a temperature of 45 ºC it is necessary to include restrictions in the model. Two restrictions regarding user comfort are included, one regarding the annual percentage of discomfort and another one limiting the time out of comfort for each hour of the day. In this way, the first restriction is imposed to a maximum of 5 % of discomfort for a year by using Equation (2). The second restriction consist on a maximum value fixed to 30 min/year for each hour of the day (00:00-24:00), which means a maximum value of almost 5 seconds per day of discomfort. Another restriction is considered in the model regarding the operation of the SHP, which is limited to 9 starts per hour. Thus, for considering the case for the optimization analysis it has to fulfill the three requirements above explained. Independently of the restrictions yet commented, the cases will also be neglected if in the case the SHP works inappropriately. It happens for big volumes of the TES and high values of scale SHP that the SHP never reaches stable conditions concerning the nominal mass flow that should circulate through the secondary circuit. It is due to the time that it remains switched on is too low. Nevertheless, this cases show efficiency performance drops (SPF$_{user}$).

$$Annual_{discomfort} = \frac{\sum m_{user\ (T<45℃)}}{\sum m_{user}} < 0.05 \quad (2)$$

2.2. Considerations and assumptions

The model for the simulation of the stratified storage tank consist on TRNSYS type 60, which is widely used and it is experimentally validated in [15]. Moreover it is defined by TRNSYS as *"the most detailed tank model available in the standard TRNSYS library"* [8]. An aspect ratio equal to 4 was assumed for the model of the tank, which is the ratio between its height and diameter. This value is usually used for tank models, such as [16], and most commercial tanks achieve or are near this value. Regarding also the TES model, a de-stratification conductivity value was included in the model. The value was calculated by using Equation (3) obtained from TRNSYS mathematical reference recommendation [8], a complete explanation of the modelling of the tank and this value can be found in [17, 18]. The value obtained corresponds to 2 W/mK.

$$k_{destratification}(W/mK) = k_{tank-wall} \cdot \frac{A_{tank}}{A_{fluid}} \quad (3)$$

It is assumed that the availability of sewage water is unlimited and always at 30ºC, which corresponds with applications such as district heating. The outlet at the evaporator is a temperature drop of 4.5K; as a result of an exhaustive study for optimizing the COP of the SHP. Limited availability of sewage water, which represents other applications, is a future work case. At the start of the simulation the tank is supposed to be full and at 50ºC.

The TES and the SHP are coupled through a direct connection. The direct connection serves as reference as the most efficient case, and in order to consider any other indirect connection option the system global efficiency percentage reduction values obtained in [19] should be applied. These values are of general application. An indirect connection is required by the EN 1717:2000 due to the risk of putting the refrigerant in potential contact with the potable water.

3. Results and discussion

In this section are presented the results for the performance indicator selected, the SPFuser. Three cases are presented depending on the control strategy selected. First, the temperature control is set on the top node of the storage tank, the following one the control is set on the second node and the last one the temperature sensor is placed in the fifth node of the storage tank. *Figure 2*, *Figure 3* and *Figure 4* respectively. Each of the control strategy cases introduced is analyzed for all the tank volumes considered varying from 0.1 m^3 to 2 m^3 and the SHP scale varying from 0.1 to 1. In this way, next are presented the results of SPF_{user} graphically for each of the control strategies and the optimal volume and SPF user for each value of scale SHP (see Table 1. *Optimal volume and* SPF_{user} *for each scale HP of the three cases analyzed.*

). It should be pointed out that not all the cases are plotted, since the ones that not comply with the restrictions commented in section 2.1. Performance indicators and comfort requirements are not included.

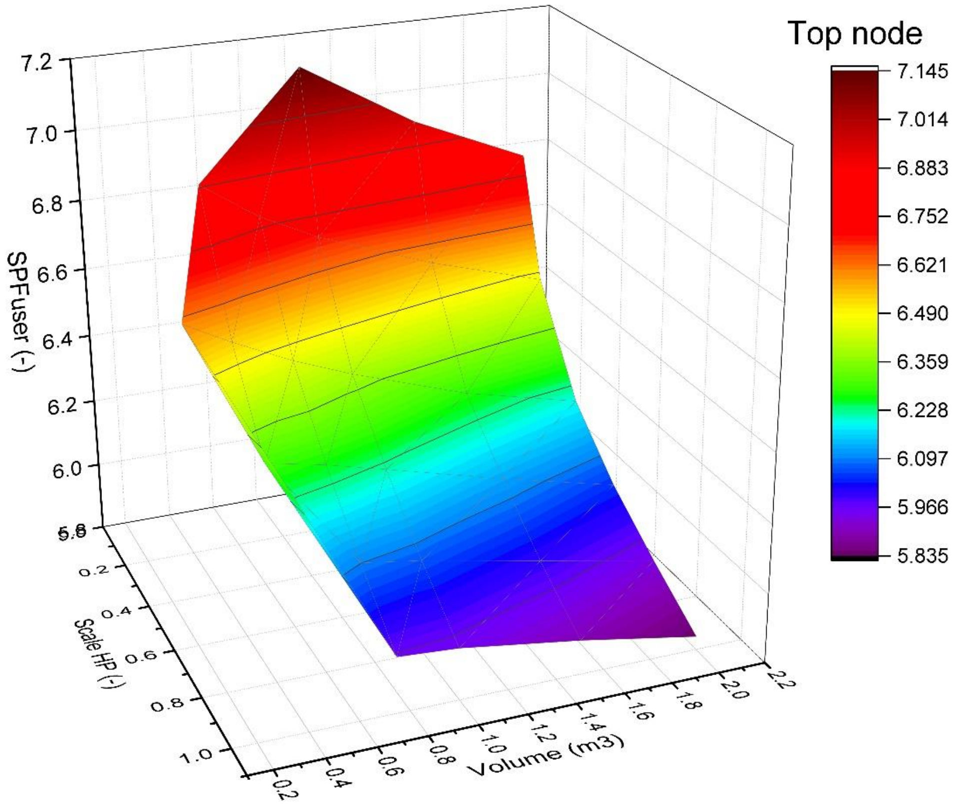

Figure 2. SPF_{user} results for the top node control strategy.

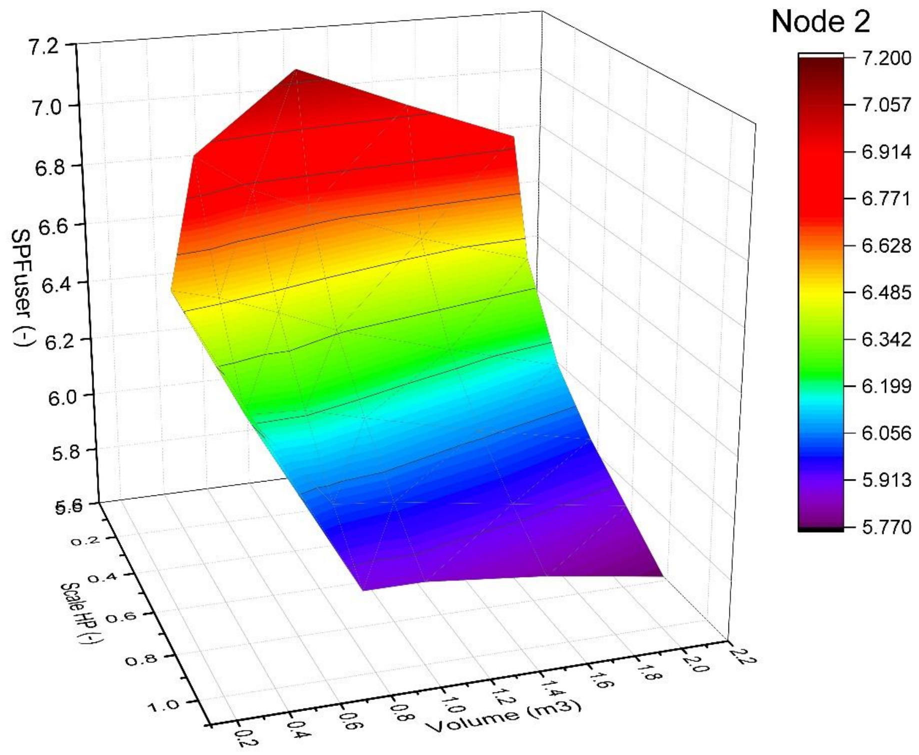

Figure 3. SPF$_{user}$ results for the node 2 control strategy.

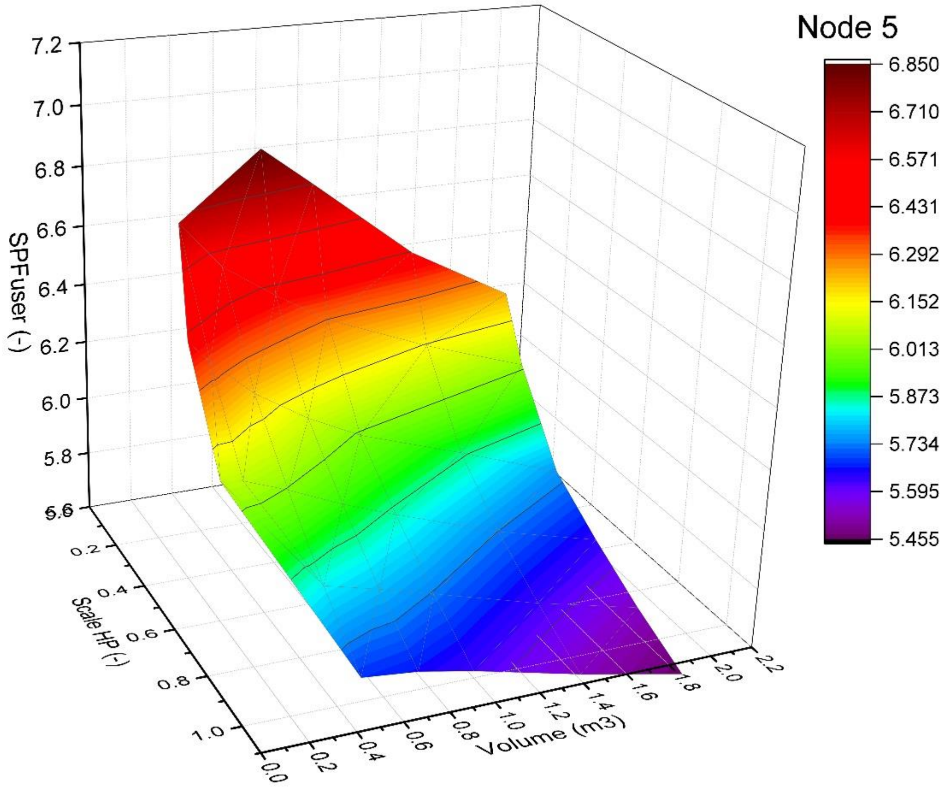

Figure 4. SPF$_{user}$ results for the node 5 control strategy.

Comparing *Figure 2*, *Figure 3* and *Figure 4* the difference in system global efficiency is the most remarkable aspect. By looking at the figures it can be concluded that the higher the control in the nodes of the tank the higher the system global efficiency. It is due to the fact of a higher volume to heat up as the sensor descends to a lower node that requires a higher number of working hours and thus a higher energy consumption by the system.

Regarding the results for the optimized variables it can be seen a common tendency between the three cases considered. Independently on the scale SHP value, the SPF_{user} decreases as the volume of the tank increases. In a similar way, as the scale SHP size increases the system global efficiency decreases. It is due to a higher energy consumption by the system since the volume to heat up increases and also both thermal losses and stratification losses increase with the volume of the tank.

In *Table 1* are presented the optimal values for the tank volume for each scale SHP along with the SPF_{user} resulting for the three cases analyzed.

Scale HP	Top Node		2nd Node		5th Node	
	Volume (m3)	SPFuser	Volume (m3)	SPFuser	Volume (m3)	SPFuser
0.1	1	7.14	1	7.1	0.75	6.85
0.2	0.5	6.89	0.5	6.88	0.3	6.68
0.4	0.3	6.61	0.3	6.54	0.2	6.41
0.6	0.5	6.29	0.5	6.22	0.2	6.08
0.8	0.75	6.10	0.75	6.02	0.5	5.83
1	0.75	5.96	0.75	5.87	0.5	5.68

Table 1. Optimal volume and SPF_{user} for each scale HP of the three cases analyzed.

The results presented in *Table 1* show also the tendencies above commented. It can be seen how the system global efficiency decreases as the volume and SHP size increase. Thus, the optimal SPF value always corresponds with the minimum tank volume that fulfills with the restrictions commented in section 2.1. Performance indicators and comfort requirements. It is due to a lower energy consumption of the system because the volume to heat up at the demand temperature of 60 ºC is much lower as low is the tank volume. Exactly, the same happens with the control strategy of the system, the SPF value is higher as lower is the sensor control position in the tank, because the volume to heat up increases.

Another remarkable aspect is the number of cases that fulfill with the three restrictions for each of the SHP sizes and cases. As the sensor position in the node decreases, more are the cases that fulfill with the restrictions. Thus, as it can be seen in *Table 1*, the case of the control in the fifth node allows to install a lower tank volume for each SHP size compared with the top node control. A similar case happens with the size of the SHP, as the size increases a lower volume tank fulfills with the restrictions, except for big values of scale SHP where instabilities produce.

Finally, an important result can be extracted from the table concerning the oversizing of the SHP. By selecting the optimal SPF value for each case, the system global energy efficiency is highly reduced as the SHP size increases from the optimal value. An energy efficiency maximum loss of 10 % and minimum of 2.25 % is observed for the top node, 18.47 % and 4.44 % for the 2nd node and 18.62 % and 2.15 % for the 5th node respectively. Regarding the oversizing of the tank volume for each value of SHP taking as reference the optimum case for each value of SHP scale, a maximum difference of 11.73 % in SPF_{user} is observed.

4. Conclusions

This work presents the comparison of different system control strategy for a water-to-water booster SHP coupled with a stratified storage tank. Using for the analysis an innovative SHP developed in the frame of the NEXTHPG European project with a variable subcooling control. In addition, the analysis of the design and sizing of the duality SHP-TES is addressed. The cases are compared in terms of system global efficiency, using the SPF_{user} as performance indicator.

The results show the control strategy of placing the sensor in the top node of the stratified storage tank as the optimal option. The optimal results of SPF are obtained for the lowest value of scale SHP and tank volume. Regarding the sizing of the SHP and tank it is advisable to proper size the SHP-tank duality since the losses in energy efficiency for an oversized SHP and optimal tank volume can lead to almost 20 %. It is also important to pay attention to the user comfort, since not all the cases considered fulfill the annual comfort requirements and neither the hourly ones.

In conclusion, it is very important to select the appropriate size of SHP for the application and then the suitable tank volume for the application and SHP size selected. Since it can lead to energy efficiency losses up to 18.47 % regarding the oversizing of the SHP and up to 11.73 % regarding the oversizing of the tank. Taking into account the system global efficiency but always guaranteeing the user comfort above all.

5. Acknowledgements

Part of the work presented was carried by Estefanía Hervás Blasco with the financial support of a PhD scholarship from the Spanish government SFPI1500 x 074478XV0. The authors would like also to acknowledge the Spanish ‘MINISTERIO DE ECONOMIA Y COMPETITIVIDAD’, thorugh the project. “MAXIMIZACION DE LA EFICIENCIA Y MINIMIZACION DEL IMPACTO AMBIENTAL DE BOMBAS DE CALOR PARA LA DESCARBONIZACION DE LA CALEFACCION/ACS EN LOS EDIFICIOS DE CONSUMO CASI NULO” with the reference ENE2017-83665-C2-1-P for the given support and “REDUCCIÓN DE LAS EMISIONES DE CO2 EN LA PRODUCCIÓN DE AGUA CALIENTE A ALTA TEMPERATURA A PARTIR DE LA RECUPERACIÓN DE CALOR RESIDUAL MEDIANTE EL USO DE UNA BOMBA DE CALOR” with the reference SP20180039.

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