OPTIMIZATION OF A THERMAL ENERGY STORAGE SYSTEM PROVIDED WITH AN ADSORPTION MODULE – A GENOPT APPLICATION IN A TRNSYS/MATLAB MODEL

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ABSTRACT

The optimization and assessment study of a thermal energy adsorption storage system is presented. The system integrates an adsorption heat storage module in a conventional hot water storage tank of a solar thermal system, operating with the silica-gel/water adsorption pair. The system was modeled using TRNSYS® and MATLAB®, and was previously assessed and improved through a set of parametric tests for each main component. In this work, the GenOpt® optimization software was used to obtain the optimal performance of the whole system. It is found that a slender and lengthy adsorber with a large number of thin fins, a thick and lengthy condenser, and an evaporator with a large number of lengthy tubes improve the system's performance, by increasing the heat transfer areas and the adsorbent mass. The performance also improves by controlling the adsorber-condenser valve only through the system's pressure and opening the evaporator-adsorber valve at the hot water setpoint temperature. The optimized system presents a 16% saving in annual backup energy consumption compared with a similar conventional storage system, thus validating the results of the previous segregated parametric study. This optimized system operates at the highest performance with the same configuration in different locations/climates, as only the inclination of the solar collector affects the results: larger inclinations improve the system's performance, by favoring its operation in Winter. Results present this system as a promising solution to increase the energy storage capacity of solar thermal systems, and potentially of systems using other primary energy sources.

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Keywords**:** Thermal energy storage; Domestic hot water; Adsorption; Silica-gel/water pair; Numerical simulation; Optimization

NOMENCLATURE

D	diameter [m]
e	thickness [m]
h	height [m]
l	length [m]
N	number
Q	heat [J]
T	temperature [°C]
V	volume [m^3]

Greek symbols

α	inclination
ΔH	heat of adsorption [J/kg]
ε	total porosity of the adsorbent bed [-]

Subscripts

ads	adsorber; adsorption
backup	backup water heater
c	condenser
conv	conventional
e	evaporator
f	fin
h	hollow
i	inner
node	domestic hot water tank node
o	outer

sg	silica-gel
solar	solar collector
sp	setpoint
t	tube
tank1	domestic hot water tank
tank2	pre-heating water tank
V1	adsorber-condenser valve
V2	condenser-evaporator valve
V3	evaporator-adsorber valve

1. INTRODUCTION

Sorption heat storage is a promising alternative to conventional heat storage systems. It is able to handle the temporary storage of thermal energy in an easier, more compact and efficient way, even for long storage periods, with negligible heat losses and high energy densities (higher than sensible or latent heat storage). Solar thermal energy, geothermal energy, biomass energy, thermal surplus energy or waste heat from several processes can be used as a heat source for thermal energy storage (TES). Sorption heat storage is thus a promising technology to integrate, or even replace, the heating obtained from fossil fuels or electric systems, reducing the CO_2 emissions and lowering the peaks of energy demand and the required energy production levels. Practical feasibility of the adsorption thermal energy storage has already been demonstrated and adsorption cycles have already been applied for that purpose in several research projects [1–10].

In this context, in an attempt to overcome the limitations of sensible TES in conventional solar systems for domestic hot water (DHW), a novel adsorption storage system was proposed in previous works [11,12]. This system combines the characteristics of the adsorption heat storage with a conventional hot water storage tank. A silica-gel adsorber, placed inside the hot water tank, stores the thermal energy received from the hot water, to give it back later as adsorption heat, while a condenser and an evaporator operate as heat sink and heat source, respectively, for the adsorption working fluid (water) phase changes. This is particularly suitable for solar energy systems, whose supply is neither possible to control nor coincident with the hot water demands. The adsorption system model was developed in MATLAB®, and interacts with the solar thermal energy system through TRNSYS®.

The performance of the TES adsorption system was previously assessed through a set of parametric tests, aimed to evaluate the behavior of the system under different geometry configurations, and mainly focusing on its individual components: water tanks, adsorber, condenser and evaporator [11]. However, this study was not fully comprehensive, as it resulted from a segregated assessment of each individual component. In this regard, it was not strictly an optimization study. Therefore, in this work, the GenOpt® optimization software is employed to jointly evaluate the influence of the different components on the performance of the thermal storage adsorption system, by interacting with the system dynamic simulation and adjusting a set of main governing parameters. This allows a better assessment of the system's optimal overall performance, and a better understanding of its components dynamics, as well as its performance in different locations/climates. The optimization study and assessment are an important step to evaluate the viability of adsorption systems, as several adsorption systems studies have already pointed out: cooling systems [13–19], heating and cooling hybrid systems [20,21], thermal heat storage systems [22–25], and desalination systems [26,27].

2. DESCRIPTION AND OPERATION OF THE ADSORPTION STORAGE SYSTEM

The main goal of the TES adsorption system is to store the thermal energy (obtained from flat solar collectors) by regenerating the adsorbent material (silica-gel) in the adsorber immersed in the DHW tank (desorption), and to give it back later as adsorption heat − through the adsorption of the previously desorbed working fluid (water). Also, during the desorption phase, the condensation heat of the desorbed vapor is recovered to preheat the cold water entering the tank, and, during the evaporation phase, low temperature heat is extracted from the ambient air. This allows to reduce the need for backup heating (usually non-renewable energy). The system configuration is depicted in Figure 1, while Figures 2, 3 and 4 present the main components for a better understanding of the parameters varying in this optimization study.

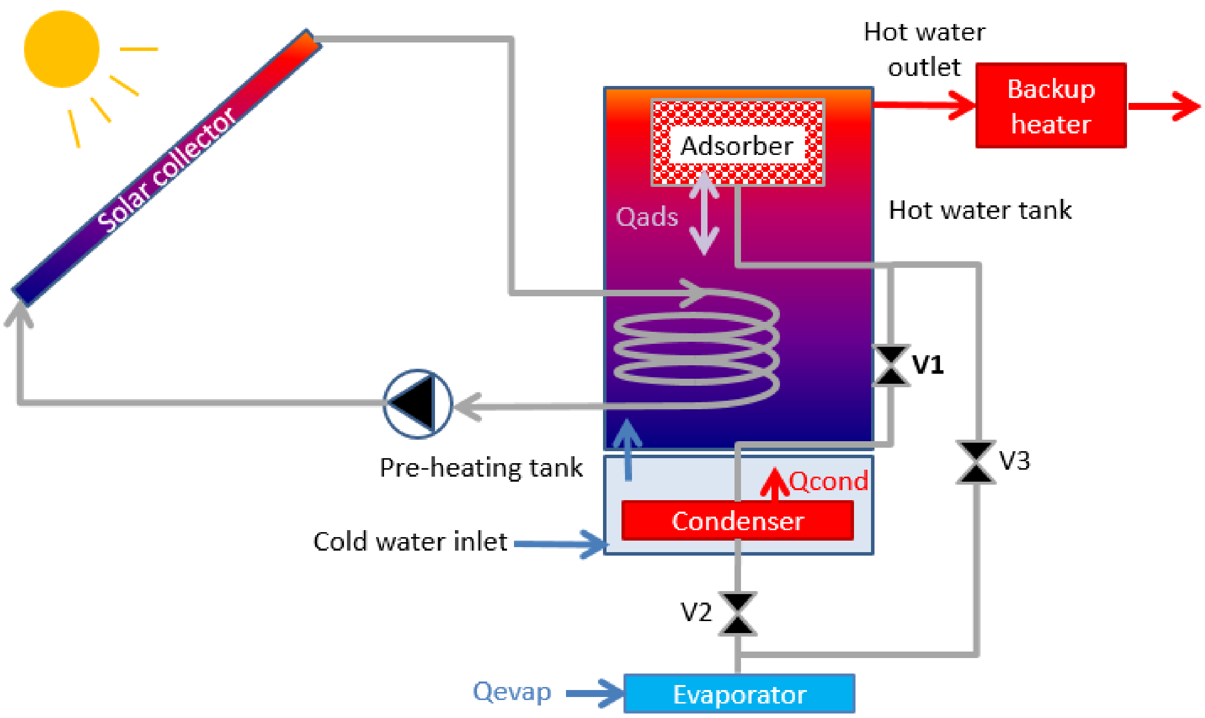

Figure 1 – Schematics of the solar thermal system for DHW production with adsorption energy storage module.

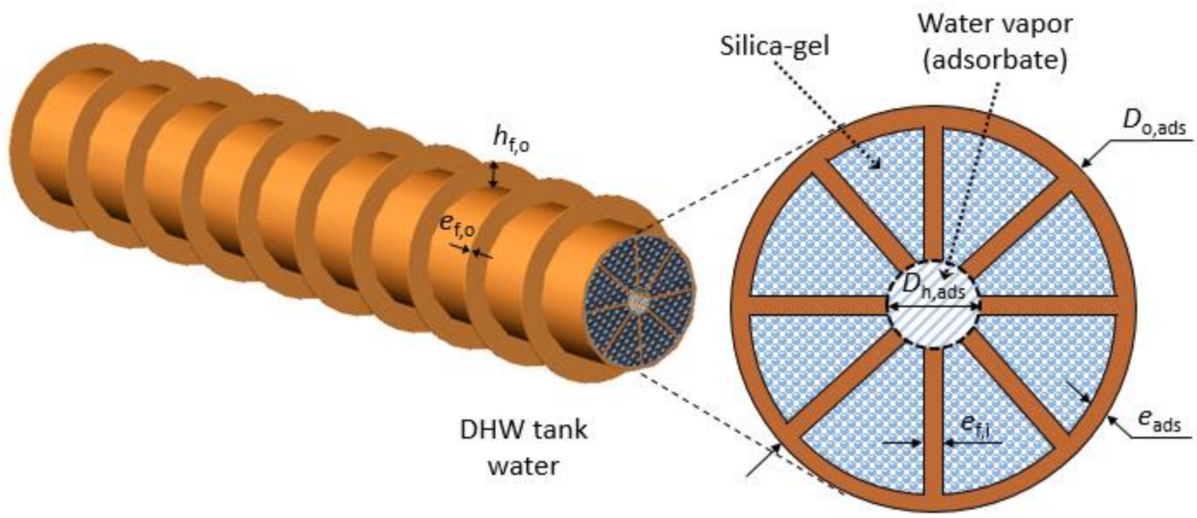

Figure 2 – Schematic of the adsorber. $D_{o,ads}$, $D_{h,ads}$, e_{ads}, are, respectively, the adsorber outer and hollow diameters; thickness, $e_{f,i}$ and $e_{f,o}$ are the inner and outer fins thickness; and $h_{f,o}$ is the outer fins height.

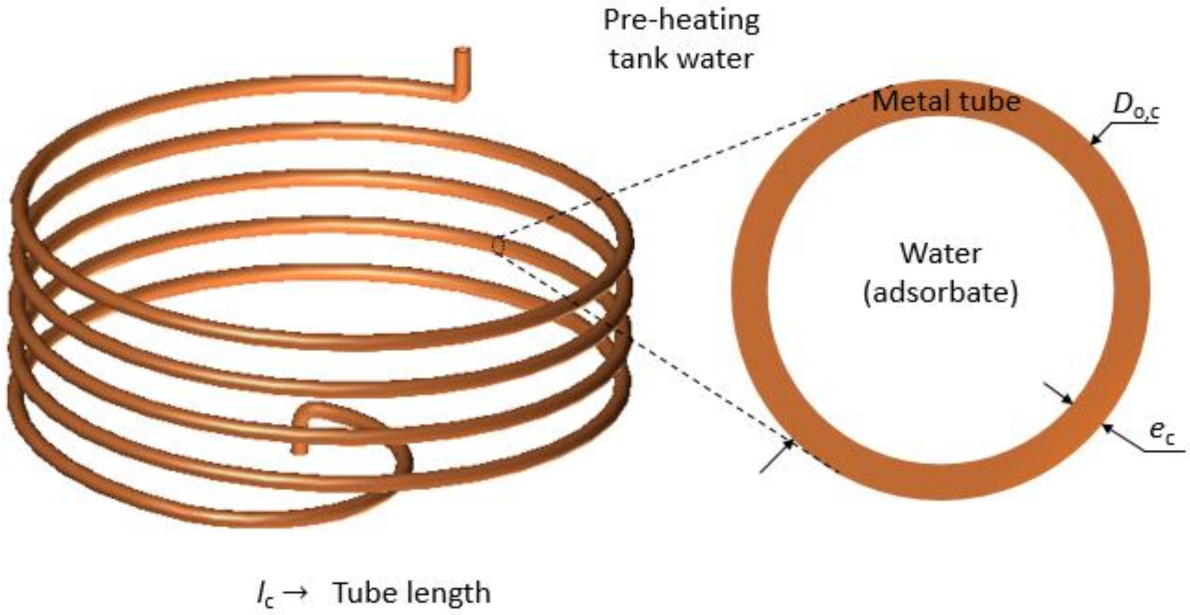

Figure 3 – Schematic of the condenser. l_c, $D_{o,c}$ and e_c are the condenser tube length, outer diameter and thickness, respectively.

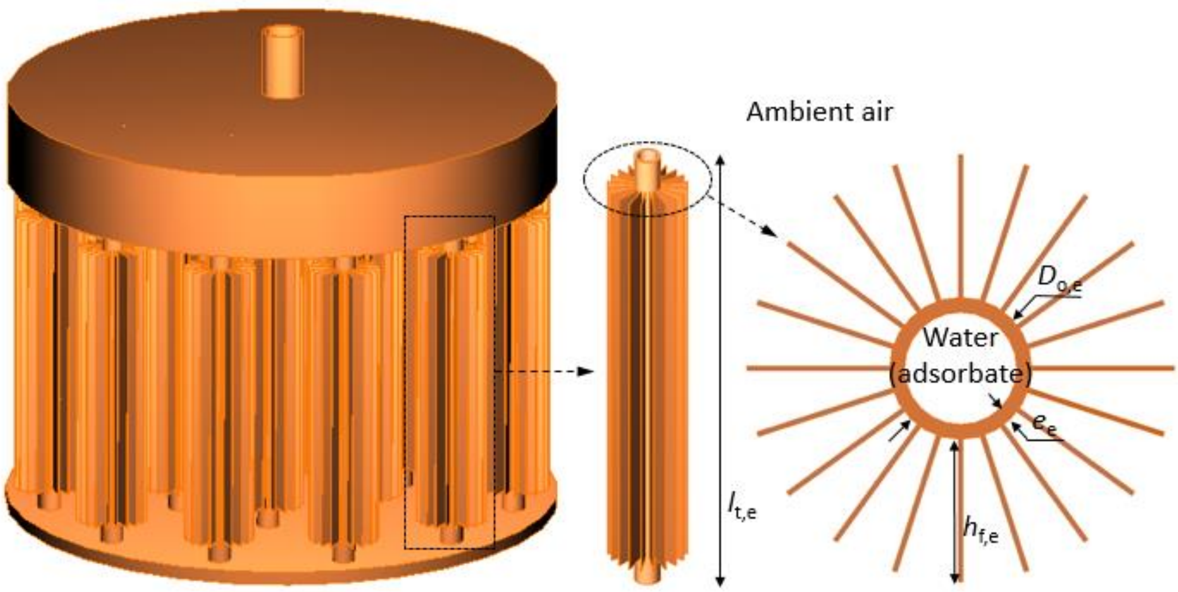

Figure 4 – Schematic of the evaporator and details of an evaporator tube. $l_{t,e}$, $h_{f,e}$, $D_{o,e}$ and e_e are the evaporator tube length, fins height, outer diameter and thickness, respectively.

During the charging phase, valve V1 is opened and the solar energy input raises the main tank water temperature, which in turn warms up the adsorber (Figure 2), releasing the water vapor contained in the silica-gel bed (desorption). The desorbed water vapor is then cooled down and liquefied in the condenser (Figure 3). The condensation heat is used to preheat the cold water in the secondary reservoir. The condensate water is drained to the evaporator (Figure 4) through valve V2, and, at the end of desorption, all the valves are closed, maintaining the adsorption module charged, even for long periods. Then, during the discharging phase, when the water temperature in the main tank drops below a specified value, valve V3 is opened, and the evaporator and the adsorber get connected. This promotes the adsorption of the water vapor, which is produced in the evaporator by extracting low temperature heat from the ambient air. The water vapor is adsorbed by the adsorbent bed, releasing the adsorption heat to the surrounding water in the main tank, thus raising its temperature. The detailed description and operation of the adsorption system can be found in [11,28].

3. DYNAMIC MODELING OF THE ADSORPTION STORAGE SYSTEM

The solar thermal system is modeled using TRNSYS® 17, a simulation software with a modular structure, dividing the system into a set of components (Types), modeled using mathematical equations programmed in FORTRAN [29]. However, TRNSYS® does not include any adsorption-related components. Therefore, the model for the adsorption module (adsorber, condenser, secondary water tank and evaporator) was built in MATLAB®, and the TRNSYS® hot water storage tank has been modified to integrate the adsorber, taking advantage of the interaction features between both TRNSYS® and MATLAB® software packages.

Details of the dynamic model of the adsorption storage module and its interaction with the solar thermal system can be found in [11,12,28].

4. PREVIOUS PARAMETRIC STUDY

The developed model was used to perform a segregated (element-by-element) sensitivity analysis of the governing parameters of the system's main components: water tanks, adsorber, condenser and evaporator [11]. Results were compared using the annual energy saving (Q_{saving}) as the leading parameter. Q_{saving} is calculated by

Equation (1) as the difference between the yearly energy consumption of the backup water heater in a conventional energy storage system and the yearly backup energy consumption provided by the system with the adsorption module.

$$Q_{\text{saving}} = Q_{\text{backup,conv,year}} - Q_{\text{backup,ads,year}} \tag{1}$$

It was found that increasing the condenser length and diameter leads to higher savings of backup heating energy, independently of the secondary tank volume. On the other hand, increasing the volume of the secondary tank has always an increasing effect on Q_{saving}, though less significant for larger volumes. As for the evaporator and considering a fixed volume, it was found that tubes with smaller diameter (implying a larger number of longer tubes) result in moderately higher Q_{saving}. Also, increasing the main tank volume (and proportionally increasing the secondary tank, adsorber and evaporator) reduces the annual consumption of backup heating energy to a minimum, after which this effect is reversed. This segregated parametric analysis allowed for improvements of 5% to 7% in Q_{saving}. However, when jointly considering the best values for all the adsorption system's components, Q_{saving} increases to 15.9%. Nevertheless, those optimal values still resulted from segregated assessments of each individual component. Therefore, an overall optimization study is required, in order to evaluate the system's performance when considering the simultaneous and combined effects of all components, and also to validate the previous segregated approach.

5. OPTIMIZATION

Based on the governing parameters considered in the previous parametric study [11], and for the same set of conditions, an overall optimization is performed to find the system's configuration leading to the lowest backup energy consumption – $Q_{backup,\text{ads}}$. The GenOpt® software was used for this purpose; it is an optimization software for the minimization of a cost function that is evaluated by an external simulation program (TRNSYS®, in this case) [30]. Therefore, the goal of this study is to simultaneous evaluate the influence of the thermal storage adsorption system parameters through an integrated assessment methodology, seeking to optimize the overall performance of the system.

5.1. Methodology

The interaction between GenOpt® and TRNSYS® requires the modification of both programs' input files (*e.g.*, identification of the cost function, location of main files, setting of output files) in order to define a proper interaction, the correct setting of the optimization options (*e.g.*, algorithm type, iterations limits), as well as the definition of the governing parameters and their variation ranges. The main optimization settings are presented in Table 1. The Generalized Pattern Search (GPS) main algorithm, which is a derivative free algorithm for multi-dimensional optimization, was selected. It defines the construction of a mesh, which is then explored according to the rules defined for the specific algorithm, in this case the GPS Coordinate Search algorithm with adaptive precision function evaluations. If no decrease in cost function is obtained on mesh points around the current iteration, the distance between mesh points is reduced and the process is repeated [30].

Table 1 – GenOpt® optimization settings.

Setting	Parameter/Value
External simulation program	TRNSYS® 17
Cost function	$Q_{backup,\mathrm{ads}}$
Maximum number of iterations	200
Maximum equal results	5
Algorithm	GPS Coordinate Search
Mesh size divider	2
Initial mesh size exponent	0
Mesh size exponent increment	1
Maximum number of steps reduction	1

In general, the optimization method consists of consecutive TRNSYS simulations ('iterations'), which attempt to minimize the desired function (the backup energy consumption – $Q_{backup,\mathrm{ads}}$), depending on the governing parameters' variation (within the defined range) and on the selected optimization algorithm. After each simulation/iteration, GenOpt® evaluates whether the targeted parameter decreases the value of $Q_{backup,\mathrm{ads}}$; if not, the evaluation will proceed with an opposite-direction variation of the targeted parameter in the following iterations, until the minimum backup energy consumption is achieved. This process is performed for the entire set of governing parameters.

5.2. Results

The governing parameters and their ranges and variation steps are presented in Table 2. The diameter values for all tubular elements vary according to standard nominal values (DN), which also correspond to standard thickness values. Regarding the evaporator tubes, for each diameter there is a given number of external fins ($N_{f,e}$), according to [31]. $f_{ads\text{-}node}$ represents the fraction of the DHW tank node occupied by the adsorber element (considering the cylindrical volume delimited by the adsorber external fins). Thus, the adsorber length (l_{ads}) is a function of this value and of the remaining adsorber external dimensions. The numbers of internal and external fins of the adsorber ($N_{f,i}$ and $N_{f,o}$, respectively) are the maximum values that allow for a 6 mm spacing between the internal fins (at their tip level) and a 10 mm spacing between the external fins. It is also considered that the diameter of the adsorbent's hollow central space ($D_{h,ads}$) – for the passage of adsorbate vapor – is 25% of the adsorber internal diameter. Therefore, the thickness (and, consequently, the mass) of adsorbent is also a function of this parameter in each case.

As for the DHW tank height (h_{tank1}), its variation implies changing also the tank's diameter (and, consequently, the pre-heating tank diameter), since the whole tank volume is considered constant (V_{tank1} = 250 L). The total volume of the pre-heating tank is considered constant (V_{tank2} = 62.5 L), so the water volume in this tank will depend only on the condenser dimensions: diameter ($D_{o,c}$) and length (l_c). In this optimization study, the variation range of l_c considered (5 m to 7 m) is such that a tube with the maximum diameter ($D_{o,c}$ = 33.4 mm) can fit inside the pre-heating tank (for l_c > 7 m this is no longer feasible). Also, knowing from the previous segregated study that larger l_c values lead to better system performances [11], values below 5 m were not considered. Regarding the setpoints of the adsorption module valves, the 'N.L.' ('Not Limited') value represent the case where their opening does not depend on the water temperature. The values of the remaining governing parameters used in the optimization study are presented in Table 3 and in Figure 5.

Table 2 – Targeted parameters on the optimization study and respective variation ranges.

Component	Parameter	Range	Variation step
Adsorber	$D_{o,ads}$ (e_{ads}) [mm]	10.16 (2.108), 12.7 (2.108), 14.13 (2.769), 16.828 (2.769), 19.368 (2.769), 21.908 (2.769)	–
	$e_{f,i}$ [mm]	1.0 – 2.0	0.5
	$e_{f,o}$ [mm]	1.0 – 2.0	0.5
	$h_{f,o}$ [mm]	0.1 x $D_{o,ads}$ – 0.3 x $D_{o,ads}$	0.1 x $D_{o,ads}$
	$f_{ads\text{-}node}$	0.5 – 0.9	0.1
Condenser	$D_{o,c}$ (e_c) [mm]	10.26 (1.727), 13.72 (2.235), 17.15 (2.311), 21.34 (2.769), 26.67 (2.87), 33.4 (3.378)	
	l_c [m]	5 – 7	1
Evaporator	$D_{o,e}$ (e_e, $N_{f,e}$) [mm]	19.05 (2.11, 16), 25.4 (2.77, 20), 48.26 (36.8, 36), 60.32 (3.91, 40)	–
	$h_{f,e}$ [mm]	0.5 x $D_{o,e}$ – 1 x $D_{o,e}$	0.25 x $D_{o,e}$
DHW tank	h_{tank1} [m]	0.7 – 1.2	0.05
Valves	$T_{sp,V1}$ [°C]	N.L., 25 – 60	5
	$T_{sp,V3}$ [°C]	35 – 55, N.L.	5

Table 3 – Parameters used in the system's dynamic simulations.

Parameter	Value
Location	Coimbra (40.20° N, 8.41° W)
Simulation time step	300 s
Simulation period	1 year
Main tank volume	250 L
Pre-heating tank volume	62.5 L
Solar heat exchanger length	10.1 m
Solar heat exchanger surface area	0.805 m^2
Consumption setpoint	45 °C
Mains water temperature	16 – 22 °C
Pump mass flow rate	186.2 kg/h
Solar collector area	3.68 m^2
Solar collector inclination	45°
Solar collector circuit upper thermostat dead band	6 °C
Solar collector circuit lower thermostat dead band	2 °C
Adsorption module components material	Copper
Silica-gel type	A (ΔH_{sg} = 2710 kJ/kg, ε_{sg} = 0.646)

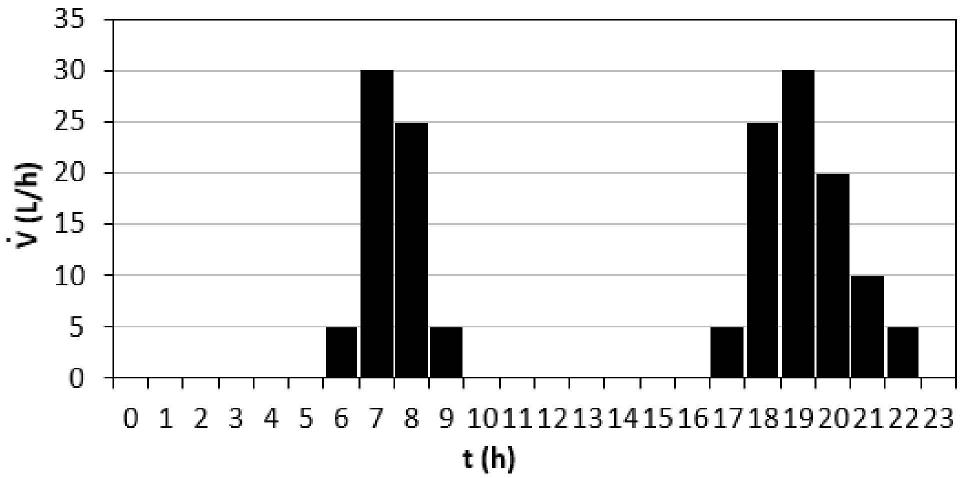

Figure 5 – Hourly water consumption profile considered for the dynamic simulations.

From this optimization study, the system's configuration for which $Q_{backup,\mathrm{ads}}$ is minimum is detailed in Table 4, and it leads to Q_{saving} = 155.4 MJ (*i.e.*, a 15.9% saving over the conventional system). While the conventional system's backup heater requires 976.5 MJ during the year to satisfy the hot water consumption needs at the defined hot water setpoint temperature (45 °C), with the optimized system the Q_{backup} value decreases to 821.1 MJ. In other words, it is possible to save in one year the energy required for heating up by 20 °C a water volume of 1855.8 L (nearly 10 times the volume of water inside the DHW tank considered in this work).

Table 4 – Optimal configuration.

Component	Parameter	Optimal value
Adsorber	$D_{\mathrm{o,ads}}$ (e_{ads}) [mm]	10.16 (2.108)
	$e_{\mathrm{f,i}}$ [mm]	1.0
	$e_{\mathrm{f,o}}$ [mm]	1.0
	$h_{\mathrm{f,o}}$ [mm]	0.1 x $D_{\mathrm{o,ads}}$
	$f_{\mathrm{ads\text{-}node}}$	0.9
Condenser	$D_{\mathrm{o,c}}$ (e_{c}) [mm]	33.4 (3.378)
	l_{c} [m]	7
Evaporator	$D_{\mathrm{o,e}}$ (e_{e}, $N_{\mathrm{f,e}}$) [mm]	19.05 (2.11, 16)
	$h_{\mathrm{f,e}}$ [mm]	1 x $D_{\mathrm{o,e}}$
DHW tank	h_{tank1} [m]	0.75
Valves	$T_{\mathrm{sp,V1}}$ [°C]	N.L.
	$T_{\mathrm{sp,V3}}$ [°C]	45
	$Q_{\mathrm{backup,ads}}$ [MJ]	821.1

Figure 6 depicts the evolution of each targeted parameter and the cost function ($Q_{backup,\mathrm{ads}}$) during the optimization run. It can be seen that internal and external adsorber fins with lower thickness ($e_{\mathrm{f,i}}$ and $e_{\mathrm{f,o}}$, respectively) tend to decrease the $Q_{backup,\mathrm{ads}}$ value, as more fins are able to fit on the adsorber, thus increasing its heat exchanging surface area and improving the performance of the adsorber system. Likewise, a lengthier and more slender adsorber is desirable, *i.e.*, with a small diameter ($D_{\mathrm{o,ads}}$), short fins ($h_{\mathrm{f,o}}$) and occupying the largest possible volume in the tank node ($f_{\mathrm{ads\text{-}node}}$), as it also accounts for a larger heat exchanging surface area, as well as for more adsorbent mass. The optimal results – $e_{\mathrm{f,i}} = e_{\mathrm{f,o}} = 1.0$ mm, $D_{\mathrm{o,ads}} = 10.16$ mm, $h_{\mathrm{f,o}} = 0.1 \times D_{\mathrm{o,ads}}$ and $f_{\mathrm{ads\text{-}node}} = 0.9$ – led to a slender and lengthy adsorber with a large number of external fins – $l_{\mathrm{ads}} = 7.7$ m, $N_{\mathrm{f,i}} = 10$, $N_{\mathrm{f,o}} = 695$ –, containing 36.9 kg of silica-gel disposed as a 37 mm-thick layer inside the adsorber tube.

A shorter water tank (lower h_{tank1}) is also found to provide better results, as it allows for a larger diameter (the whole tank volume is considered constant), thus allowing to accommodate more evaporator tubes. Together with evaporator tubes of small diameter ($D_{\mathrm{o,e}}$) and tall fins ($h_{\mathrm{f,e}}$), that increases the heat exchanger surface area, thus improving the adsorber system's performance. In this case, the optimal values – $h_{\mathrm{tank1}} = 0.75$ m, $D_{\mathrm{o,e}} = 19.05$ mm and $h_{\mathrm{f,e}} = 1 \times D_{\mathrm{o,e}}$ – led to a large number of longer evaporator tubes ($N_{\mathrm{t,e}} = 90$). On the other hand, it is desirable a lengthier and thicker condenser (with greater l_{c} and $D_{\mathrm{o,c}}$), *i.e.*, with an increased heat exchange area. The optimization results led to $l_{\mathrm{c}} = 7$ m and $D_{\mathrm{o,c}} = 33.4$ mm.

Finally, a lower $Q_{backup,\mathrm{ads}}$ is achieved if the temperature control of valve V1 (tank water temperature setpoint) is suppressed, as that will allow for the desorption phase to start earlier. The temperature setpoint of valve V3 that suits better the $Q_{backup,\mathrm{ads}}$ reduction was found to be 45 °C, which corresponds to the defined hot water setpoint temperature. A more detailed sensitivity analysis for each parameter can be found in references [11,12,28].

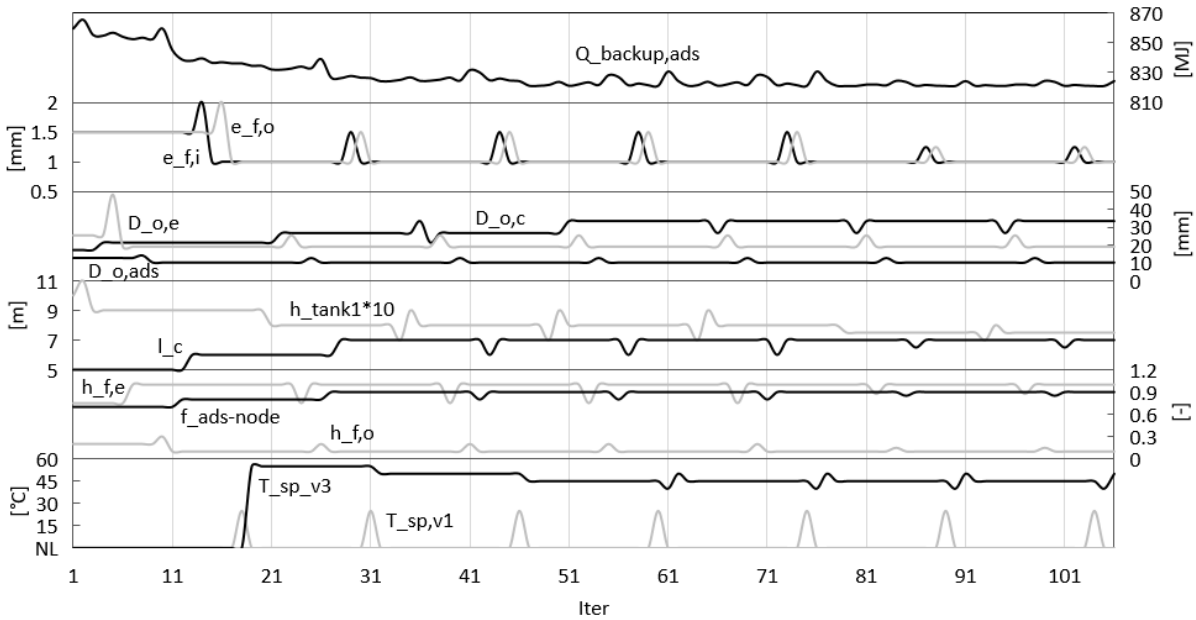

Figure 6 – Evolution of the optimized parameters and cost function throughout the optimization run.

Each annual simulation run for the optimization process took an average of 1h 57min to complete, on an Intel i3-2100 3.10 GHz dual core processor desktop computer with 4.00 GB RAM. 106 iterations were required to reach convergence, with a total of nearly 143h of optimization time.

5.3. System location

An optimization study regarding the system location was also performed. Three distinct locations in Portugal were selected, comprising an intermediate, a colder and a warmer climate: Coimbra (40.20° N, 8.41° W), Bragança (41.81° N, 6.76° W) and Faro (37.02° N, 7.93° W), respectively. The governing parameters to optimize and their ranges and variation steps are the same as presented in Table 2. In addition, the solar collector inclination is also a governing parameter: ±10° relatively to the location's latitude, with steps of 1°. The remaining simulation parameters are the same as presented in Table 3. For each location, the resulting system configuration that minimizes $Q_{backup,\mathrm{ads}}$ is presented in Table 5, and compared to the $Q_{backup,\mathrm{conv}}$, which corresponds to the backup heater consumption of a similar conventional system with the same solar collector inclination for each location considered.

For the Coimbra case, 156 iterations were required to reach convergence, taking an average 1h56min for each yearly simulation, with a total of nearly 253h of optimization time. For the Bragança case, 159 iterations were required to reach convergence, taking an average 1h59min for each yearly simulation, with a total of nearly 251h of optimization time. Finally, for the Faro case, 143 iterations were required to reach convergence, taking an average 1h51min for each yearly simulation, with a total of nearly 221h of optimization time.

Table 5 – Optimal parameters for the different locations selected.

		Bragança	**Coimbra**	**Faro**
Component	**Parameter**	**Optimal value**	**Optimal value**	**Optimal value**
Adsorber	$D_{o,ads}$ (e_{ads}) [mm]	10.16 (2.108)	10.16 (2.108)	12.7 (2.108)
	$e_{f,i}$ [mm]	1.0	1.0	1.0
	$e_{f,o}$ [mm]	1.0	1.0	1.0
	$h_{f,o}$ [mm]	0.1 x $D_{o,ads}$	0.1 x $D_{o,ads}$	0.1 x $D_{o,ads}$
	$f_{ads\text{-}node}$	0.9	0.9	0.9
Condenser	$D_{o,c}$ (e_c) [mm]	33.4 (3.378)	33.4 (3.378)	33.4 (3.378)
	l_c [m]	7	7	7
Evaporator	$D_{o,e}$ (e_e, $N_{f,e}$) [mm]	19.05 (2.11, 16)	19.05 (2.11, 16)	19.05 (2.11, 16)
	$h_{f,e}$ [mm]	1 x $D_{o,e}$	1 x $D_{o,e}$	1 x $D_{o,e}$
DHW tank	h_{tank1} [m]	0.75	0.75	0.75
Valves	$T_{sp,V1}$ [°C]	25	N.L.	N.L.
	$T_{sp,V3}$ [°C]	45	45	45
Solar collector	α_{col}	51°	49°	47°
	$Q_{backup,ads}$ [MJ]	1278.5	813.2	232.0
	$Q_{backup,cov}$ [MJ]	1463.9	952.8	296.0
	Q_{saving} [%]	12.7%	14.6%	21.6%

As it can be seen from Table 5, for the intermediate climate case (Coimbra), the results are similar to the previous cases (Table 4) without considering the solar collector inclination as a target governing parameter. In addition, the resulting larger solar collector inclination indicates that the adsorption storage system performs better in Winter conditions (the Sun is lower in the sky), when the heating needs are higher. This leads to more adsorption cycles performed by the system, and thus to a greater amount of adsorption heat provided to the water, reducing the backup energy requirements. In this case, Q_{saving} decreases (14.6% *vs.* 15.9%) because the optimized results show a decrease of $Q_{backup,ads}$ (813.2 MJ *vs.* 821.1 MJ) and $Q_{backup,conv}$ as well (952.8 MJ *vs.* 976.5 MJ), for a 49° solar collector inclination, in comparison with the previous results (45° inclination).

For the colder climate case (Bragança), the results are analogous to Coimbra's in most of the parameters, including the larger solar collector inclination. The difference lies in $T_{sp,V1}$ = 25 °C, which indicates that it is advantageous to promote the desorption phase only when the water temperature in the tank rises above 25 °C. This means that the adsorber-condenser valve V1 should be controlled to open when the water temperature reaches 25 °C, thus preventing the solar heat input to be used for desorption while the water is still not warm enough. Moreover, as expected, the heating needs are higher in this case, due to the colder climate of Bragança. Even so, the adsorption storage system provides an annual backup saving of almost 13%.

For the warmer climate case (Faro), the results are again similar to Coimbra's, including the larger solar collector inclination. The difference lies in $D_{o,ads}$ = 12.7 mm, which is only slightly larger than in the previous cases (10.16 mm), leading to a slightly shorter adsorber with longer fins. In this case, the heating needs are much smaller due to the warmer climate, and the adsorption storage system can provide an annual backup saving of 21.6%.

The first optimization results (Section 5.2) led to the best adsorption system configuration, while the location/climate changes only led to minor differences in specific parameters. The best results derived from large solar collector inclinations, by favoring the system´s operation during Winter conditions, when the heating needs are higher.

6. CONCLUSIONS

The optimization and assessment of a solar thermal energy storage system provided with an adsorption module was presented. The selected optimization tool was the GenOpt® software. The conducted study allowed to jointly evaluate the influence of several components' governing parameters of the TES system on its backup energy consumption ($Q_{backup,\mathrm{ads}}$), by minimizing the $Q_{backup,\mathrm{ads}}$ cost function in the system's simulation program – TRNSYS® (which interacts with a MATLAB® code to solve the adsorption module and water tanks model equations). It was concluded that to reduce the backup heater energy consumption it is desirable to have: (*i*) a slender and lengthy adsorber, with a large number of thin fins; (*ii*) a thick and lengthy condenser; (*iii*) an evaporator with a large number of lengthy tubes, requiring water tanks with a larger cross-section (thus shorter, for the same volume), hence increasing the heat transfer areas of the heat exchangers and the mass of adsorbent; (*iv*) to control the valve V1 opening only through the adsorption system's pressure, and not through the water temperature, and to match the valve V3 temperature control to the defined hot water setpoint temperature. This set of conditions resulted in an optimized adsorption storage system with the lowest backup energy consumption – a 15.9% saving relatively to a similar conventional water storage system.

Considering different locations/climates it was also concluded that the solar collector inclination has a prevailing influence on the results. Therefore, the optimized system is able to operate at the highest performance in different locations, with very similar values of the analyzed parameters, provided that the collectors' inclination is conveniently adjusted (as for any DHW solar system). Besides, larger inclinations favor the system operation in Winter, when the heating demand is higher, thus improving the system's performance.

These conclusions allow for a deeper understanding of the operation of the TES adsorption system and the influence of its individual components on the system's overall performance, attesting for the importance of the integral optimization study and assessment. The results also validate the conclusions of the previous segregated parametric study, confirming that the element-by-element approach previously adopted, by trial and analysis of results, was essentially correct. Therefore, this paper, in conjunction with the results presented in previous works [11,12,28], points the way for the advantageous application studies of this energy storage system provided with an adsorption module. Besides, with this work it was possible to explore the potential of the GenOpt® optimization software applied to a heavy multi-parameter model (based on the TRNSYS® - MATLAB® coupling).

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