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Performance Analysis of a Solar DHW System with Adsorption Module Operating in Different World Locations

Marco S. Fernandes ^{1,*}, Vítor A. F. Costa ², Gonçalo J. V. N. Brites ¹, Adélio R. Gaspar ¹ and José J. Costa ¹

¹ ADAI-LAETA, Department of Mechanical Engineering, University of Coimbra, P-3030 788 Coimbra, Portugal; goncalo.brites@uc.pt (G.J.V.N.B.); adelio.gaspar@dem.uc.pt (A.R.G.); jose.costa@dem.uc.pt (J.J.C.)

² TEMA (Center for Mechanical Technology and Automation), Department of Mechanical Engineering, University of Aveiro, P-3810 193 Aveiro, Portugal; v.costa@ua.pt

* Correspondence: marco.fernandes@adai.pt; Tel.: +351-239-790-714; Fax: +351-239-790-701

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Abstract: A numerical study was conducted on the performance of a solar domestic hot water storage system with an adsorption module operating in seven different world locations. The base system was optimized for Portuguese conditions and, without changing the system itself and the water consumption profile, its performance was investigated by altering local installation and operating conditions and solar collector inclination angles. The overall dynamical model of the system was used for numerical simulations. The improved performance of the system was assessed by the reduction achieved on the annual energy consumption of a backup water heater when compared with a similar conventional energy storage system (without an adsorption module). The results showed that the best performances were obtained in locations where winter and summer are clearly defined, especially locations where winters are colder, and with solar collectors' inclination angles larger than the local latitude, except for locations with low latitudes, where solar collectors' inclination angles are not so relevant to the system performance. It was also discussed how the performance results must be carefully analyzed, as for low-latitude locations the absolute savings are in fact smaller even if their relative values are of the same order or even higher than for higher-latitude locations.

Keywords: solar DWH; adsorption; heat storage; energy efficiency; climate conditions; numerical simulation

1. Introduction

Currently, the main environmental challenges worldwide are to increase the share of renewable energy sources in final energy use and achieve an increase of energy efficiency in order to contribute to reducing greenhouse gas emissions. One of the most promising measures is to increase the utilization of solar energy. However, due to its intermittent nature, there is a need for thermal energy storage technologies in most of areas where solar energy is utilized [1,2]. This is especially relevant to domestic hot water (DHW) systems. Water heating is still a large share of the total energy consumption of households worldwide [3]. For example, it represents 19% of the total energy consumption of households in the United States [4] and 14.8% of the total energy consumption of households in the European Union [5]. Therefore, if this energy demand is fulfilled with the help of solar water heater systems, it will help to increase energy efficiency, decrease fossil fuels dependency and reduce greenhouse gas emissions. Actually, the energy efficiency in the water heating sector has increased by 25% worldwide since 2000, and it is estimated to increase by 43% until 2040 [6], for which developing

more efficient solar thermal energy storage solutions that also increase the share of renewable heating systems is a necessity.

In general, thermal energy storage can be accomplished through sensible, latent, or thermochemical (e.g., sorption) processes. Compared with conventional sensible and latent thermal energy storage processes, adsorption can deal with the temporary thermal energy storage in an easier, more compact and efficient way, even for long periods, with high energy densities and low or even null heat losses. In addition, adsorption thermal energy storage systems are able to use a wide range of heat sources, e.g., solar thermal, biomass, geothermal, thermal surplus, or available waste heat. It is thus a promising alternative to conventional heat storage systems and also to integrating or partially or fully replacing heating from fossil fuels or electric systems [2,7–10]. This technology is still under development, since different issues need to be solved at both material and system levels, to become a feasible technology for commercial applications. However, adsorption heat storage is gaining more and more attention in the scientific community as an emerging technology; its viability has already been demonstrated, and different adsorption cycles have already been applied for thermal energy storage in several research works [1,8,11–15].

In this context, a new adsorption thermal energy storage system was presented and optimized in previous works [16–19], trying to reduce some limitations of conventional sensible DHW heat storage systems. It is especially appropriate for solar energy systems, where energy supply does not typically coincide with hot water demands and is not possible to control. The system combines the main features of the adsorption thermal energy storage with a conventional hot water storage tank. It is composed of a hot water tank, an adsorber (filled with silica gel) located inside the hot water tank, a condenser, and an evaporator. Water is the working fluid in the adsorption system. The adsorber stores the thermal energy received from the hot water in the storage tank (desorption heat) and releases it later to heat up the water in the tank (adsorption heat). The condensation of the operating fluid in the condenser releases heat into the storage tank, and the evaporation of the operating fluid in the evaporator extracts heat from the ambient.

This work aimed to evaluate the performance of the DHW storage system with an adsorption module, previously optimized for the Portuguese climate conditions, when operating in some representative locations around the world. It was thus an assessment on how a given product behaves in distinct world locations without further modifications of the system itself. However, the particular characteristics of each location were taken into consideration regarding the system's installation (solar collectors' inclination), the weather data, and the mains water temperature entering the system.

2. Materials and Methods

2.1. Description and Operation of the Adsorption Storage System

The main purpose of the thermal energy storage system with an adsorption module is to take advantage of the adsorption process to store part of the thermal energy obtained from solar collectors in an effective and compact way. The thermal energy is firstly used to regenerate the adsorbent material (desorption) and retrieved later to heat up the water in the storage tank, when the previously desorbed working fluid is adsorbed by the adsorbent (adsorption). Additionally, the adsorption module works like a heat pump, capturing low-temperature heat from the surrounding ambient air and releasing it at higher temperatures to heat up the water in the storage tank. The considered system with the adsorption module has the following specificities: (i) the adsorber is immersed in the DHW tank; (ii) during the desorption phase, the cold intake water is preheated by the recovered condensation heat of the desorbed vapor; and (iii) during the evaporation phase, heat is captured from the surrounding ambient air. The system's main objective is to reduce the backup heating needs (usually electric heating) and likewise to reduce the nonrenewable energy consumption.

The system, presented in Figure 1, consists of a conventional hot water storage reservoir with an adsorber unit immersed inside. The adsorber is filled with an adsorbent material and is connected to a

condenser. This heat exchanger is immersed in a secondary water tank to preheat the intake of cold mains water and is connected to an evaporator exposed to the ambient air. These main components (adsorber, condenser, and evaporator) form a closed airtight circuit operating under moderate vacuum conditions. A first valve (V1 in Figure 1) separates the adsorber unit from the condenser, a second valve (V2 in Figure 1) separates the condenser from the evaporator, and a third valve (V3 in Figure 1) separates the evaporator from the adsorber. A backup electric heater is used at the DHW reservoir outlet to heat up the water, when the temperature setpoint for hot water consumption is not reached in the storage tank. The adsorption working pair in the system is silica gel/water.

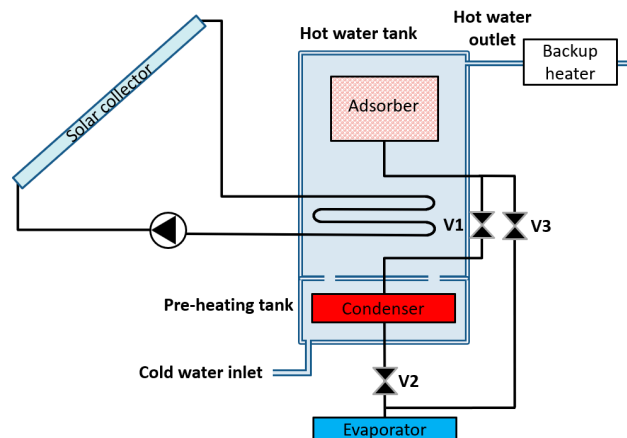


Figure 1. Solar thermal domestic hot water system with an adsorption module.

The adsorber, filled with silica gel, is horizontally immersed in the top section of the DHW tank, to take advantage of the thermal stratification effect. The desorbed water vapor is condensed in the condenser during the desorption phase. The condenser is immersed in the secondary water reservoir, where the cold mains water is preheated before entering the main storage tank. The evaporator receives and stores the condensed water coming from the condenser. This water is later vaporized at low pressure, during the adsorption phase, extracting low-temperature heat from the surrounding ambient air (similarly to what happens in a heat pump).

The detailed description and operation of the system can be found in Reference [16], while a study regarding its optimization is presented in Reference [18]. The three phases of the system's operation are briefly described as follows:

(a) Charging

At the beginning of the charging phase, all valves remain closed, and heat (solar energy) enters the storage tank. Afterward, when the water temperature in the main tank surpasses a specified value, V1 opens (this setpoint prevents the solar heat input to be used for desorption, while the water in the main reservoir is still not warm enough). The adsorber receives the thermal energy from the hot water in the main tank, and the water vapor is released from the silica gel bed (desorption). The desorbed vapor is subsequently condensed in the condenser, and the resultant condensation heat is recovered to preheat the cold water in the secondary tank.

When the charging phase ends, V1 closes, while V2 allows, before it closes, the drainage of the condensate water to the evaporator, where it is stored until the discharge phase starts.

(b) Storage

After the adsorber is energy-charged (after desorption) and the condensate water is in the evaporator, all valves remain closed. Hence, the adsorption process does not take place, since the silica gel (in the adsorber) and the water (in the evaporator) are kept separate. Therefore, the adsorption module remains charged as an adsorption potential with no energy losses, even for long periods.

(c) Discharging

Once the adsorber is energy-charged and the evaporator–adsorber connection is allowed (by opening V3, when the water temperature of the main tank drops below a specified value—V3 setpoint), it promotes the adsorption of the water vapor produced in the evaporator at low temperature and low pressure. While adsorbing this vapor and as long as the water in the main tank is colder than the adsorber, the adsorption heat is released from the adsorber to heat up the water in the main tank. During the evaporation phase, low-temperature heat is extracted from the ambient air. Afterwards, when the adsorption process ends, all valves are closed again, and the adsorption module is ready to initiate a new energy-charging phase.

2.2. Dynamic Modeling of the DHW Adsorption System

The solar thermal system was modeled using TRNSYS[®] 17 (Figure 2), a type of simulation software with a modular structure, where the system is divided into a set of components (types), modeled using mathematical equations programmed in FORTRAN [20]. Since TRNSYS[®] does not present any components to model/simulate the adsorption process, the model for the adsorption module (adsorber, condenser, evaporator, and preheating water tank) was elaborated in MATLAB[®], and the original TRNSYS[®] hot water storage reservoir was altered in order to integrate it, taking advantage of the interaction capabilities between both programs.

The detailed description of the dynamic model of the adsorption storage module and its interaction with the solar thermal system are presented in References [16,17].

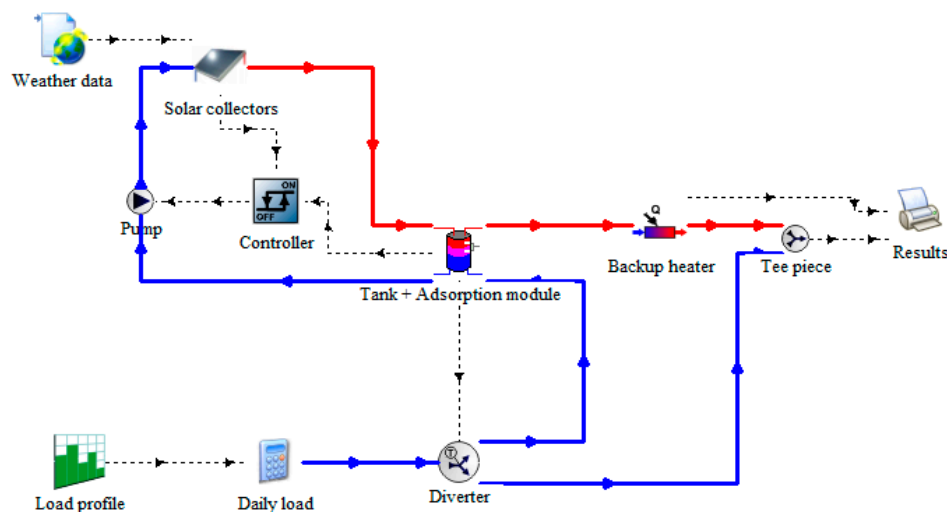


Figure 2. TRNSYS[®] diagram of a solar thermal system with an adsorption module. Solid lines represent water flow, while dashed lines represent information flow.

2.3. Methodology

The operation of a system designed and optimized for the Portuguese conditions was simulated for different world locations. Seven capital cities, each taken as representative of different continents in both the Northern and Southern Hemispheres, were considered: Beijing, China (39.9° N, 116.4° E), Baltimore (Baltimore was selected instead of Washington D.C., since there were no available climate data for the latter. Therefore, the data from the closest main city were used in this study.), USA (39.3° N, 76.6° W), Lisbon, Portugal (38.7° N, 9.1° W), New Delhi, India (28.6° N, 77.2° E), Brasília, Brazil (15.8° S, 47.9° W), Cape Town, South Africa (33.9° S, 18.4° E), and Canberra, Australia (35.3° S, 149.1° E). These locations were chosen, since they represent the capital cities of important countries located in different continents and hemispheres, where the system's operation can be of interest. On the other hand, most of these countries also have high energy savings concerns and represent high potential of worldwide

science readers interested in exploring and testing the present system. The weather data for these locations were downloaded from the EnergyPlus website [21]. For each location, the effect of the solar collectors' inclination was also investigated, considering a variation of $\pm 10^\circ$ in relation to the location's latitude, with steps of 5° , i.e., analyzing 5 different collectors' slopes per location.

The adsorption system's performance was evaluated by the difference between the yearly energy consumption of the backup water heater using a conventional energy storage system (i.e., without an adsorption module) and that using a system with an adsorption module, which is written as:

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

where Q_{saving} is the annual backup energy saving, i.e., the annual adsorption system's performance. $Q_{\text{backup,conv,year}}$ is the yearly energy consumption of the backup water heater using a conventional energy storage system, and $Q_{\text{backup,ads,year}}$ represents the yearly energy consumption of the backup water heater using a system with the adsorption module.

The main parameters considered in this study are presented in Table 1 and Figure 3. The adsorber, the condenser and evaporator dimensions, and the valves' setpoints corresponded to its optimal configuration for Portuguese conditions, defined in Reference [18]. These parameters were similar for all the assessed locations. On the other hand, the mains water temperature entering the system varied according to the weather data for each location.

The dataset with the results of the solar DHW system with adsorption module performances operating in the seven world locations and the respective climate data is publicly available online (see Supplementary Materials, hosted at Figshare [22]).

Table 1. Parameters considered in the study.

Parameter	Value
Simulation time step	300 s
Simulation period	1 year
Main tank volume	250 L
Main tank height	0.8 m
Preheating 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
Pump mass flow rate	186.2 kg/h
Solar collector area	3.68 m ²
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

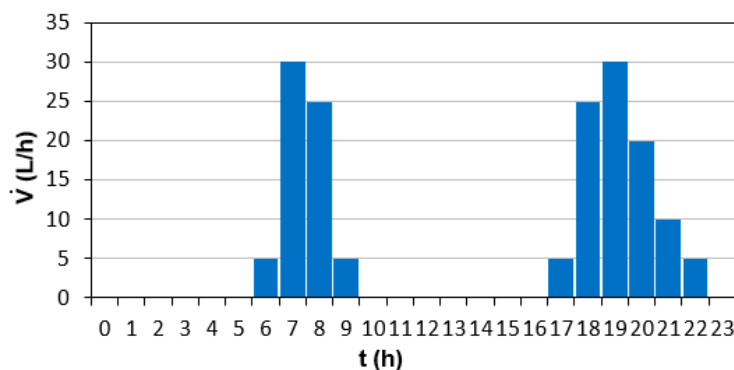


Figure 3. Hourly water consumption profile considered in the study [23].

3. Results and Discussion

Figure 4 presents a comparison between the annual energy consumption of the backup water heater in a conventional DHW solar system and that in a DHW solar system with an adsorption module for five solar collector slopes in the seven assessed locations. The locations were sorted in descending order of latitude. For each collector inclination, the annual backup energy saving (Q_{saving}) is presented on top of the respective bars in Figure 4, in both absolute (MJ) and percentual values. It should be noted that the scales of the ordinates are not the same for all the locations.

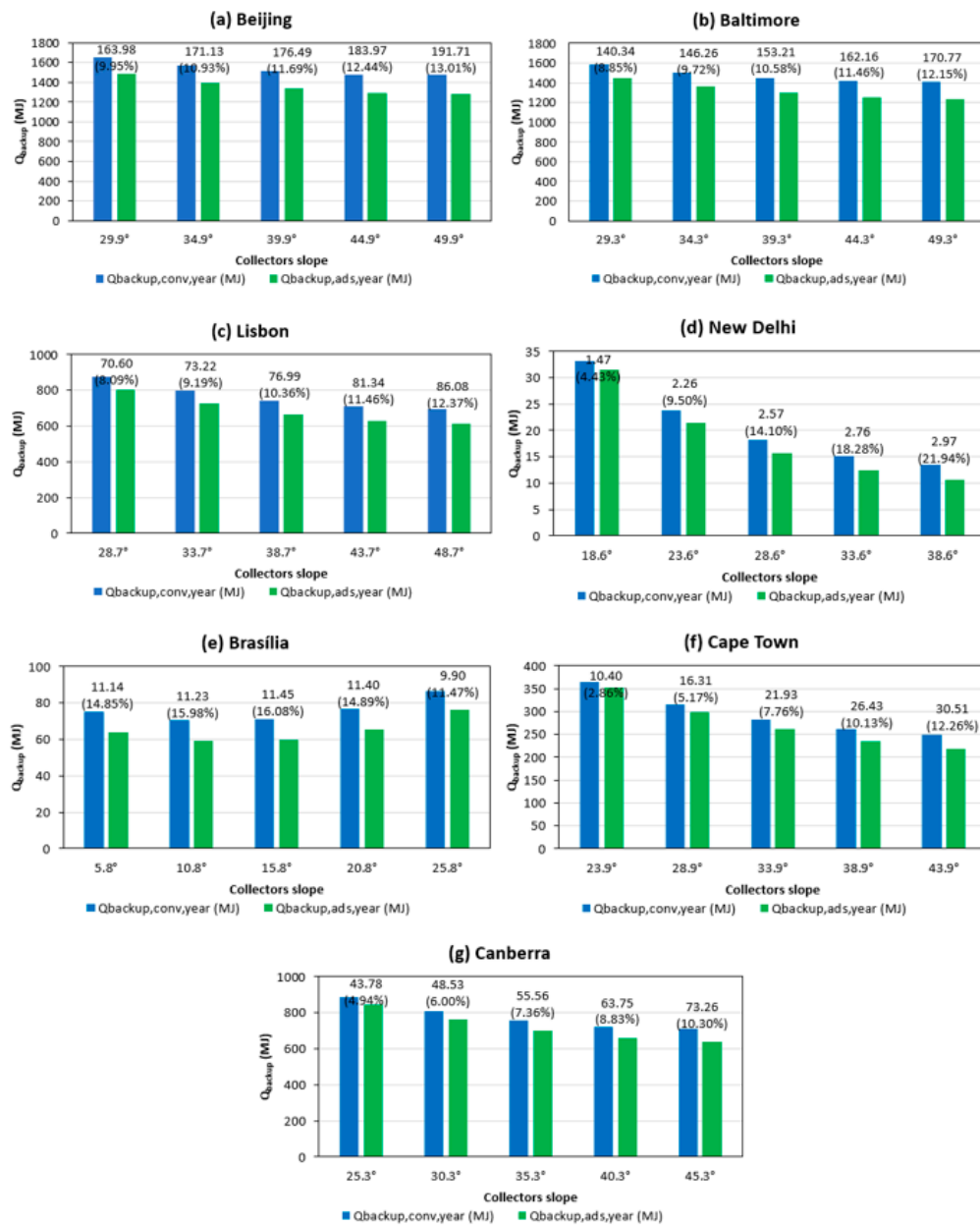


Figure 4. Comparison of yearly energy consumption of the backup water heater (Q_{backup}) using a conventional DHW solar system (blue bars) and that using a DHW solar system with an adsorption module (green bars) for different solar collector slopes in the seven assessed locations: (a) Beijing; (b) Baltimore; (c) Lisbon; (d) New Delhi; (e) Brasília; (f) Cape Town; (g) Canberra. The annual backup energy saving Q_{saving} is presented on top of the bars in both absolute (MJ) and percentual (%) values (taking $Q_{\text{backup,conv,year}}$ as a reference).

A similar evolution is observable in most of the locations: higher collector slopes lead to lower energy consumptions for both the conventional system and the one with an adsorption module and result in higher energy savings (Q_{saving}). Therefore, the best results were obtained for large solar collector inclinations, thus favoring the system’s operation during winter, when the heating needs are higher. The exception is Brasília (see Figure 4e), where this behavior was only noticed until the collector slope was increased to the intermediate level and was then inverted with further increase of the collector slope. This seems to be related with Brasília’s latitude—15.8° S, which is lower than that of the remaining locations and between the Tropics ($\pm 23.5^\circ$). There, the solar zenith angle is always high, leading to higher solar radiation throughout the year (see Figure A1 in Appendix A). Therefore, there is little gain by varying the solar collectors’ slope, as opposed to what happens for locations at higher latitudes (the remaining assessed locations), where the solar zenith angle is considerably lower in winter.

It is noticeable that at the warmer locations (New Delhi, Brasília, and Cape Town), despite the fact that the percentual energy savings are of the same order of magnitude, the absolute values of Q_{saving} are much lower than in the remaining locations. Therefore, considering a similar investment cost for the adsorption system, there seems to be little advantage in installing such a system at these warmer locations, since the effective energy savings are much lower, within the corresponding massive payback periods.

The yearly solar radiation available at different locations and the corresponding minimum values of Q_{backup} (with and without the adsorption module) and maximum values of Q_{saving} are displayed in Figure 5. The Q_{backup} and Q_{saving} values can present significant differences for locations at similar latitudes: these values are clearly smaller in Lisbon in relation to those in other locations at similar latitudes—Beijing and Baltimore. This is due to the solar radiation availability in Lisbon (5880 MJ/year/m² in the horizontal plane), which is higher than in the other locations—5025 MJ/year/m² in Beijing and 5358 MJ/year/m² in Baltimore—, thus leading to lowering backup energy consumptions. Accordingly, locations with less available solar radiation tend to present higher Q_{backup} and Q_{saving} values, i.e., the system with an adsorption module operates with higher performance in these locations. This renders a very strong Pearson correlation coefficient (ρ) of -0.94 between the maximum absolute value of Q_{saving} ($Q_{\text{saving,max}}$) and the available horizontal solar radiation (Table 2). The exception to this trend is Brasília, seemingly due to its low latitude, with similar solar radiations in the horizontal plane and in a plane with an inclination equal to the location’s latitude, and a constant mains water temperature throughout the year (see Figure A1 in Appendix A).

Table 2. Pearson correlation coefficient (ρ) between the maximum absolute value of Q_{saving} ($Q_{\text{saving,max}}$) and different locations and climates parameters.

Parameter	ρ
Latitude	0.73
Horizontal solar radiation	-0.94
Solar radiation in a plane with an inclination equal to a location’s latitude	-0.85
$T_{\text{min,year}}$	-0.89
ΔT_{year}	0.81

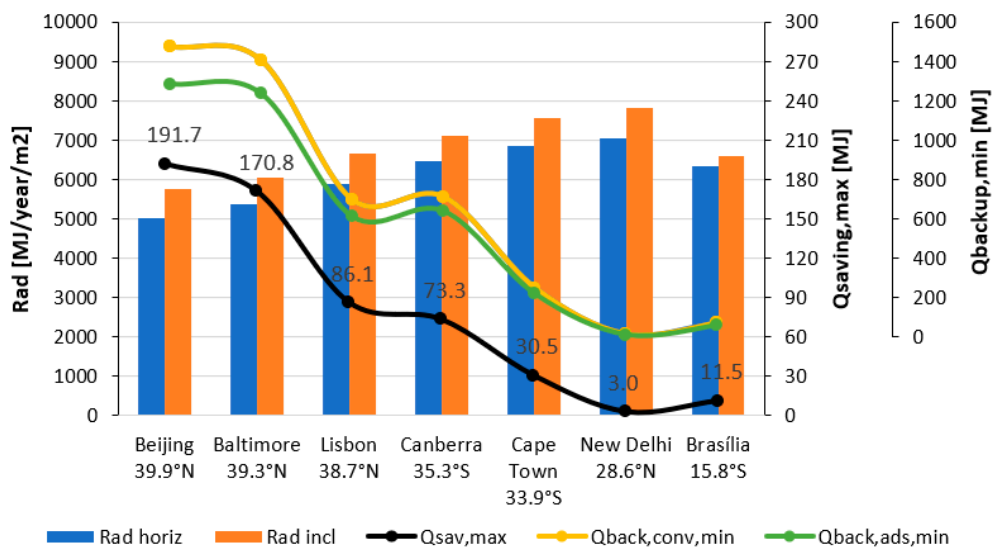


Figure 5. Yearly solar radiation values for both the conventional and adsorption systems, with the corresponding maximum values of Q_{saving} presented for each location.

Overall, the system with an adsorption module presents higher performances in locations where winter and summer are clearly defined, and especially in locations, where winters are colder (higher latitudes), like Beijing and Baltimore and, in a smaller scale, Lisbon and Canberra, as can be seen in Figures 4, 5 and A1 (Appendix A). Additionally, the solar collectors of the system operating at these high latitudes must be oriented with inclinations higher than local latitudes, in order to present the highest performance. In other words, the system’s performance is lower for lower latitudes and tends to increase for higher latitudes—locations with a low minimum annual temperature, $T_{min,year}$, and a large yearly temperature amplitude, ΔT_{year} . This is noticeable given the strong ρ coefficients between $Q_{saving,max}$ and (a) the latitude (0.73, which indicates a better performance for higher latitudes), (b) $T_{min,year}$ (−0.89, which represents a better performance for lower minimum yearly temperatures), and (c) ΔT_{year} (0.81, pointing to a better performance for higher annual temperature amplitudes), as presented in Table 2.

Additionally, a detailed yearly evolution of the best Q_{saving} for each location (corresponding to the best solar collector slope) is presented in Figure A2 (Appendix A). These results allow one to observe when and in which way the system with an adsorption module is more or less effective than its conventional counterpart. It can be seen that, for locations at higher latitudes, Q_{saving} tends to increase gradually throughout the year, thus leading to an advantage over the conventional system during all, or at least most of, the year and resulting in higher annual (final) values. In contrast, the rising evolution of Q_{saving} is much less distinct for locations at lower latitudes, sometimes adding up only during limited periods/seasons, thus leading to lower annual energy savings. In the case of New Delhi, the fact that it presents the highest yearly solar radiation (both in the horizontal and inclined planes), combined with a higher mains water inlet temperature (see Figure A1 in Appendix A), leads to a situation for which the proposed system is not an advantage: very low Q_{backup} and almost null Q_{saving} . On the other hand, in Brasília, the mains water temperature is not so high, which combined with median solar radiation values leads to a more distinct evolution of Q_{saving} , especially in the periods of decreasing solar radiation (Figure A2 in Appendix A) and thus to a higher annual Q_{saving} than in the case of New Delhi.

It is also noticeable that in the locations where the system with an adsorption module is more effective (i.e., all the locations except New Delhi and Brasília), Q_{saving} tends to rise more distinctively during winter. The exception is Beijing, where Q_{saving} adds up steadily throughout the year, given the lowest yearly solar radiation and the comparatively lower inlet temperature of the mains water (see Figure A1 in Appendix A). Compared to Beijing, Baltimore presents similar ambient and mains

water temperature evolutions and only slightly higher solar radiation values. However, the fact that the solar radiation is higher during the summer months leads to a lesser difference between $Q_{\text{backup,conv}}$ and $Q_{\text{backup,ads}}$, thus resulting in a less prominent Q_{saving} evolution during that period. The evolution for Lisbon is identical to that in Baltimore (Figure A2 in Appendix A), except for the lower Q_{saving} values at each timestep (and thus the resultant annual savings—170.8 MJ in Baltimore versus 86.1 MJ in Lisbon), since the solar radiation and mains water temperature values tend to be higher in the Portugal's capital throughout the year. On the other hand, the temperatures and the solar radiation evolutions are very similar between Cape Town and Canberra (Figure A1 in Appendix A); however, the solar radiation is slightly higher in the summer months in Cape Town (especially between November and February), and the mains water temperature is also higher. This leads to a higher yearly solar radiation (Figure 5) and a less prominent (or even nonexistent) Q_{saving} evolution during the summer period (Figure A2 in Appendix A), which accounts for a smaller annual value of Q_{saving} —30.5 MJ in Cape Town compared to that of 73.3 MJ in Canberra.

In order to further improve the system performance in the colder regions, where the energy savings are higher, one would need to modify the system configuration (which is out of the scope of the present study). In this regard, considering the parameters listed in Table 1, the system efficiency would possibly improve by increasing the solar collector area, since more solar energy would be gathered and stored during the periods with higher availability of solar radiation. However, additional care must be taken, since the adsorption module dimensions would probably need to follow this increment to be able to store the thermal energy surplus. This could also lead to the need of increasing both tanks' volumes, in order to fit the adsorption module. Therefore, this assessment may not be straightforward as it would seem to be, and further studies are required to properly analyze this effect.

4. Conclusions

The inclusion of an adsorption module into a solar DWH system is an effective way to improve its performance. Although such systems are usually developed and optimized to operate under certain specific conditions, they can effectively operate in different locations, provided that the installation conditions are suitably adapted. In this case, the easiest installation parameter that can be changed is the solar collector's inclination angle. Thus, the best solar collector's inclination angle for each location and how the system performs when operating under each location particular conditions remain to be determined.

A solar DWH system previously optimized to operate in the Portuguese conditions was analyzed when installed and operated in seven different locations around the world, representative of the locations with similar latitudes and climatic conditions, and its performance was evaluated by numerical simulation. For each particular location, the best solar collector's inclination was assessed.

The results indicated that the best solar collector's inclination angle is not the local latitude and that some deviation must be considered for better performances. It was observed that, in general, the best performances were obtained for the solar collector's inclination angles larger than the local latitude. This favors the system's operation under winter conditions, when heating needs are higher. However, for low latitudes, the solar collector's inclination angle deviation relative to the latitude is not so relevant. Locations with less available solar radiation require higher yearly energy consumptions of the backup water heater, but present also higher Q_{saving} , thus indicating that the system with an adsorption module operates with a higher performance there.

It should also be retained that, for the warmer locations with low latitudes, care must be taken when assessing the system's performance improvement associated to the use of the adsorption module only in terms of the percentual increase of Q_{saving} . This percentual increase can be relatively high for these locations, even if the absolute value of this reduction is in fact low. However, it is the absolute value of the obtained energy consumption reduction that is relevant to investment decisions.

These results allow for a deeper understanding on the system's performance under different local installation and operating conditions by considering a limited number of representative locations.

The results can thus serve as a starting point for further studies aiming to extend this work to other locations, in order to statistically assess the system's performance throughout the world. In this line, if the system configuration is altered (as opposed to the present assumption of "as is" system), further studies are required to properly evaluate the optimal system configuration for each location.

Supplementary Materials: The performance dataset of a solar DHW system with an adsorption module operating in seven world locations and respective climate data are available online at URL <https://doi.org/10.6084/m9.figshare.10048961>, hosted at Figshare [22].

Author Contributions: Conceptualization, V.A.F.C., M.S.F., J.J.C., and A.R.G.; methodology, M.S.F. and G.J.V.N.B.; software, M.S.F.; formal analysis, M.S.F. and G.J.V.N.B.; investigation, M.S.F.; writing of the original draft preparation, M.S.F.; writing of review and editing, M.S.F., V.A.F.C., J.J.C., A.R.G., and G.J.V.N.B.; visualization, M.S.F.; supervision, V.A.F.C.; project administration, V.A.F.C., J.J.C., and A.R.G.; funding acquisition, A.R.G. and V.A.F.C.

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Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A



Figure A1. Evolutions of the average global horizontal solar radiation, the average daily ambient temperature, and the average daily mains water temperature throughout the year at the seven assessed locations: (a) Beijing; (b) Baltimore; (c) Lisbon; (d) New Delhi; (e) Brasília; (f) Cape Town; (g) Canberra.

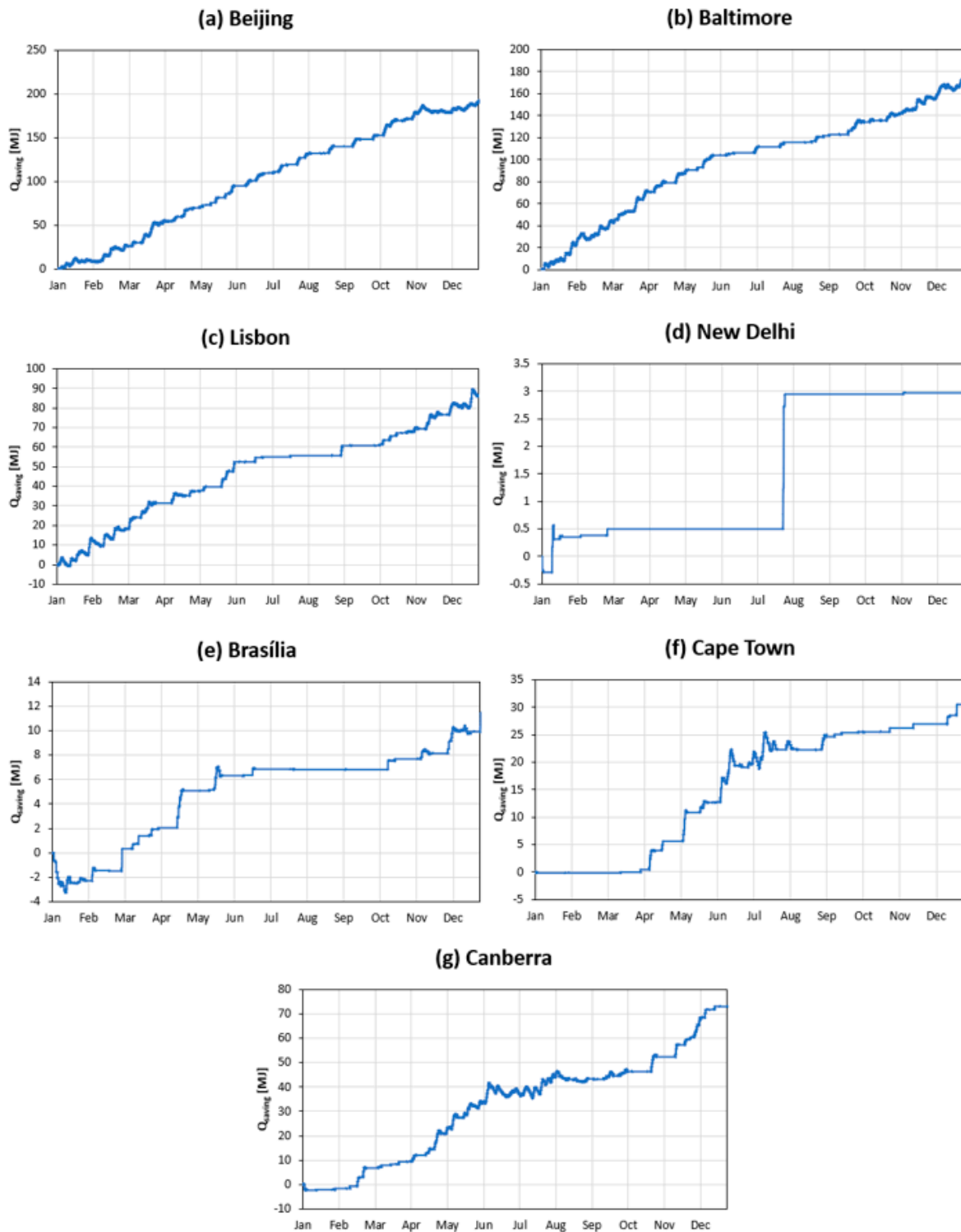


Figure A2. Evolutions of the best annual Q_{saving} throughout the year for the locations considered: (a) Beijing; (b) Baltimore; (c) Lisbon; (d) New Delhi; (e) Brasília; (f) Cape Town; (g) Canberra.

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