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DEVELOPMENT OF A TRNSYS MODEL FOR ANALYSIS OF DYNAMICAL BEHAVIOR OF A BOREHOLE THERMAL ENERGY STORAGE (BTES) FOR SOLAR THERMAL ENERGY

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Abstract. *The aim of this work is to develop a TRNSYS model for the analysis of the dynamical behaviour of borehole thermal energy storage (BTES) for solar thermal energy. Firstly, real monthly consumption data is converted into hourly data based on heating degree days for a case study located in Madrid. The results were verified with a TRNSYS boiler-model. The final model has been obtained through the assembly of different submodels namely a DHW model, a heating model and finally its integration with the BTES model. Outputs of the DHW model were verified in compliance with the Código Técnico de Edificaciones. Sizing of the different components was carried out taking into account the demand curve and the ideal solar fraction expected. Sizing of the BTES system was calculated according to the surplus energy and maximum capacity of discharge. An analysis of dynamical behavior of the BTES is performed by changing the value of different parameters in order to assess the variation in the solar fraction. After several simulations it can determine how oversized the system was. Finally, it obtains the best configuration of the BTES system for our case of study through simulations.*

Keywords: *Seasonal Energy Storage, Borehole thermal energy Storage, TRNSYS, simulation.*

1. INTRODUCTION

Solar thermal energy technologies offer good potential for production of heat for residential space heating and domestic hot water production. It can be shown that the amount of solar radiation incident on the roof of a typical home exceeds its energy consumption over a year. However, offsets and intermittence of the solar radiation make difficult to achieve the maximum performance of a solar system. Thermal Energy Storage is aimed at improving the performance of the solar system taking into account these issues. On the one hand, short thermal energy storage is the alternative to solve the intermittence issue and diurnal offsets and, on the other hand, seasonal thermal energy storage (STES) is the alternative to take advantage of the energy surplus in summer in order to use it in winter. According to the mechanism of storage there are three types of technologies for STES (Pinel et al.): Chemical, latent and sensible. The first two have not been applied for residential heating applications to date, whereas, the third has, with several technologies available. Among principal sensible thermal energy storage technologies are (IEE): Tank Thermal Energy Storage (TTES), Pit Thermal Energy Storage (PTES), Borehole Thermal Energy Storages (BTES), Aquifer Thermal Energy Storages (ATES) .In this scope, Madrid seems to be an excellent scenario for applying this kind of technologies because of the high heating demand in winter, in addition to the high solar radiation in summer. Therefore, this project intends to develop a TRNSYS (Klein, S. A. 2004) model in order to evaluate through simulations the performance of a specific technology of STES, known as Borehole thermal energy storage (BTES), in a solar thermal system. For this project, data corresponding to a macrocommunity named *Altamira*, located in Madrid, will be used as a case study.

2. BACKGROUND

Seasonal storage of solar thermal energy for space heating purposes has been under investigation in Europe since the mid-1970s within large-scale solar heating in countries as Sweden, Denmark and Germany. Thanks to several European programs, such as Solarthermie 2000 in Germany or EC-THERMIE in Sweden, several pilot Central Solar Heating Plants Seasonal Storage (CSHPSS) have been built to study the feasibility of the different STES technologies. Table 1 summarizes some of these projects with their principal features.
European projects has been planned to achieve a solar fraction around 50% after 5 years operation. Through the parameter observations of different systems it can see the performance of each one. The followings projects have been monitored for 10 years: In the case of the Friedrichshafen (TTES) project the design solar fraction was 43%. However, the maximum value reached is 33% after 10 years. In Neckarsulm project (BTES), the design solar fraction was 50% but the maximum value reached was 44.8% after 8 years of operation. In Rockstock project (ATES), the design solar fraction was 62 % and the maximum value was 57%, reached after 5 years of operation (Bauer et al. 612-623). Figure 1 shows the solar fraction behaviour for the aforementioned projects.

Table 1. Technical Data of STES projects (Bauer, Marx et al. 2010)

PROJECT	Type of STES	HEATED AREA,(m^2)	HD(1) (MWh/a)	SOLAR COLLECTOR AREA (m^2)	TYPE OF SOLAR COLLECTOR	SF(5)	VOLUME OF STORE (m^3)
Neckarsulm, DE	BTES	20000	1663	5000	FPC(2)	50%	63400
Anneberg, SE(6)	BTES	9000	1080	3000	FPC(2)	60%	60000
Okotoks, CA(7)	BTES	52 Houses	528	2293	FPC(2)	***90%***	35000
Hamburg, DE(8)	TTES Hot Water	14800	1610	3000	FPC(2)	49%	4500
Friedicshafen, DE(8)	TTES Hot Water	39500	4106	5600	FPC(2)	47%	12000
Chemnitz,DE(8)	PTES Gravel-Water	4680	573	2000	ETC(3)	42%	8000
Rostock, DE (8)	ATES	7000	497	1000	SR(4)	62%	20000
Attenkirchen, DE(8)	Hybrid: BTES and PTES	6200	487	836	FPC(2)	55%	10500

(1)HD: Heat Demand, (2)FPC: Flat Plate Collector,(3)ETC: Evacuated Tubular Collector, (4)SR: Solar Roof, (5)SF: Solar fraction (calculated values for long Time Operation), (6)SE: Sweeden, (7)CA: Canada, (8)DE: Gemany

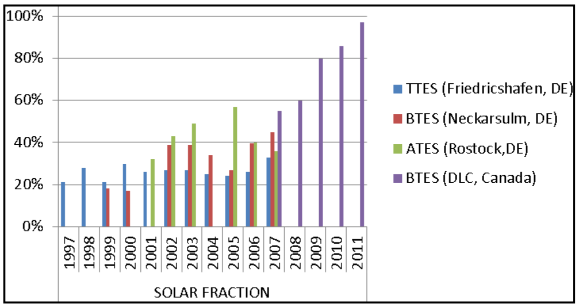


Figure 1. Solar Fraction behavior regarding to STES

On the other hand, the Canadian project in Okotocks Canada was planned to achieve a solar fraction of 90% in the same time. The data obtained from the monitoring showed that, after 5 years of operation, it reached a solar fraction of 97% (Sibbitt et al. 856-865).

In general, the decision to use a certain type of STES mainly depends on the local conditions, and primarily, on the geological and hydrogeological situation in the ground below the respective construction site. For all types, but particularly for ATES and BTES, a preliminary geological examination of the store site is essential. Approval of the water authorities must be obtained at an early stage. If different technologies are possible, an economic optimization should be carried out with the building costs for the different types of STES and the heat deliveries of the solar systems should be taken into account (Schmidt, Mangold, and Müller-Steinhagen 165-174).

3. METHODOLOGY

In order to develop a TRNSYS model for analysis of dynamical behavior of a BTES for solar thermal energy, the data of real consumption of the macro community Altamira located in Madrid are be used as input data for the models so as to have a reference base. Monthly data of the Altamira case ("Web Macrocommunity Altamira.") is analyzed in order to obtain hourly data as the input data in the TRNSYS models. Heating degree days method is used to estimate the Energy demand curve. Subsequently, a heat load model is set up with TRNSYS using conventional energy sources so as to verify the hourly data obtained. After data verification, TRNSYS sub models are set up and assembled into the BTES system as follows. Firstly, a solar thermal generator using Flat plate collectors to supply the domestic hot water (DHW) consumption; secondly, a solar thermal generator to supply heating and DHW with a short term storage and, finally, the integration of the solar thermal generator for heating and DHW with the BTES model. Finally, the sizing of the components for BTES model is carried out in order to perform the analysis of the dynamical behavior of the borehole thermal energy storage for solar thermal energy. The parameters of the system are changed in order to determine the best configuration for the case study. The obtained results are compared with others BTES projects in the literature in order to analyze the feasibility of this kind of projects in places with climatic conditions similar to Madrid.

3.1 DATA ALTAMIRA PROJECT

The heating and DHW for the community is supplied by a thermal central plant from where it is distributed to 41 communities through 15 sub centrals, one per each building (Data supplied by the Macrocomunity Altamira). Table 2 shows the Altamira data of the community.

Table 2. Data Altamira Project

Installed Capacity		Efficiency system	Annual Fuel (PCI) Consumption				Dwellings			People	
23.3 MW		0.8	23089 MWh				2750			8000	
Real data consumption Altamira Project on 2011											
Date	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Average Temperature Monthly	6,3	7,7	11,0	12,8	16,8	22,6	25,0	24,6	20,3	15,6	9,6	6,6
Real Fuel (PCI) consumption MWh	4.272	3.317	3.388	992	706	564	499	445	535	1.266	3.028	4.078

Based on the *Código Técnico de Edificaciones* and according to the Altamira Data community the DHW consumption is calculated in order to divide the heating and DHW consumption from the total real consumption. Table 3 shows the results.

Table 3. Heating and DHW demand in Altamira

Based on DHW calculation from CTE and real Altamira DATA		
Heating demand	14758 MWh	80%
DHW	3713 MWh	20%
Total heat demand	18471 MWh	100%

Specific data, such as the global heat transfer coefficient of a building, are rarely available; however, it is possible to have its mean primary energy consumption. This can be used to estimate a heating curve of hourly demand as follow: using the total HDD (Heating Degree Days) can be estimated the daily energy consumption, with this data, the hourly consumption can be estimated according to the behavior of the users in their profile daily schedule.
In order to obtain the accurate base temperature, it proceed to try with some daily base temperatures calculated with the Bizze Software (Sustainable Energy Ltd. 2005) in order to determine the curve that best fits the real monthly curve demand. Table 4 shows the obtained mean square errors (MSE) for different testing temperatures. For illustration, Fig. 2 compares some estimated curve to the real demand curve (red). The lowest MSE is obtained with a base temperature of 17 ºC, so this is the recommended base temperature for the particular studied case.

Table 4. Media Square Errors regarding Real Heating Curve Vs Base Temperature

Month	Base Temperature				
	15.5 (ºC)	16.5 (ºC)	17 (ºC)	18 (ºC)	20(ºC)
1	2,01E-04	2,64E-05	2,22E-06	4,42E-05	4,56E-04
2	9,13E-05	2,45E-05	6,63E-06	4,15E-06	1,13E-04
3	5,21E-04	5,23E-04	5,31E-04	5,69E-04	6,74E-04
4	9,82E-05	2,33E-04	3,13E-04	5,01E-04	8,87E-04
5	1,06E-06	2,57E-05	5,32E-05	1,41E-04	4,32E-04
6	7,93E-06	1,56E-12	1,29E-06	1,59E-05	8,96E-05
7	4,26E-05	3,57E-05	3,67E-05	2,11E-05	7,57E-07
8	1,01E-05	6,88E-06	4,40E-06	1,54E-06	1,44E-06
9	9,36E-06	3,57E-07	4,89E-07	1,48E-05	9,51E-05
10	9,43E-07	3,18E-05	6,05E-05	1,19E-04	3,00E-04
11	9,09E-04	7,16E-04	6,51E-04	5,67E-04	5,26E-04
12	1,08E-03	5,18E-04	3,26E-04	8,49E-05	4,33E-05
AVERAGE MSE	2,48E-04	1,78E-04	1,66E-04	1,74E-04	3,02E-04

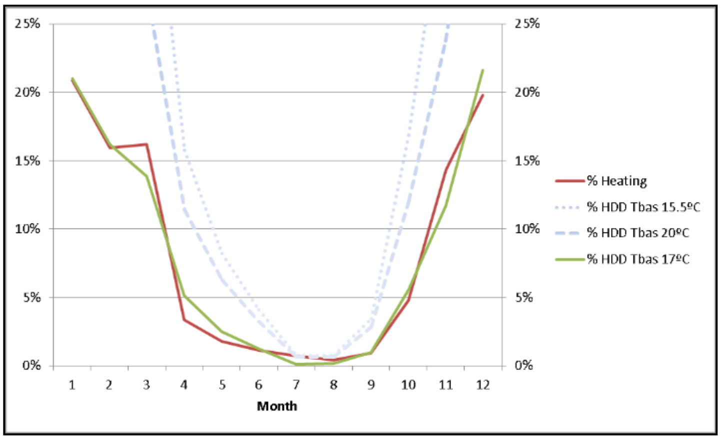


Figure 2. Curves heating degree days normalized

3.2 DEVELOPMENT OF A TRNSYS BTES MODEL FOR SOLAR THERMAL ENERGY

TRNSYS sub models are set up and assembled into the BTES system. TRNSYS domestic hot water (DHW) model is created for calculating the energy savings that it can obtain if it installs a solar system for DHW. Figure 3 shows the TRNSYS model.

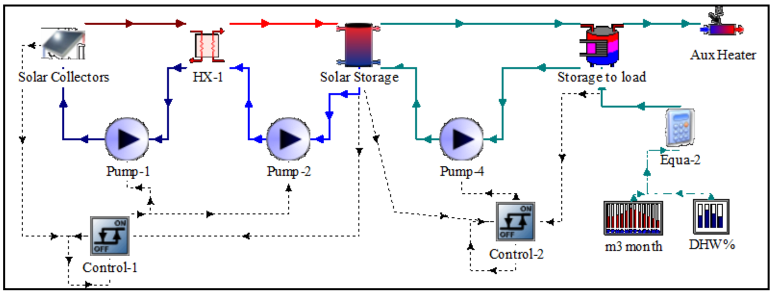


Figure 3. TRNSYS DHW Model

Figure 4 shows the results of the simulation. The blue curve shows the outlet temperature of the load storage and the red curve the set point temperature corresponding to 60 ºC. The brown curve shows the auxiliary energy required for the system. According to the simulations the solar fraction obtained based on the data of the CTE is about 68%. It expected to obtain 70%, as established by the CTE.

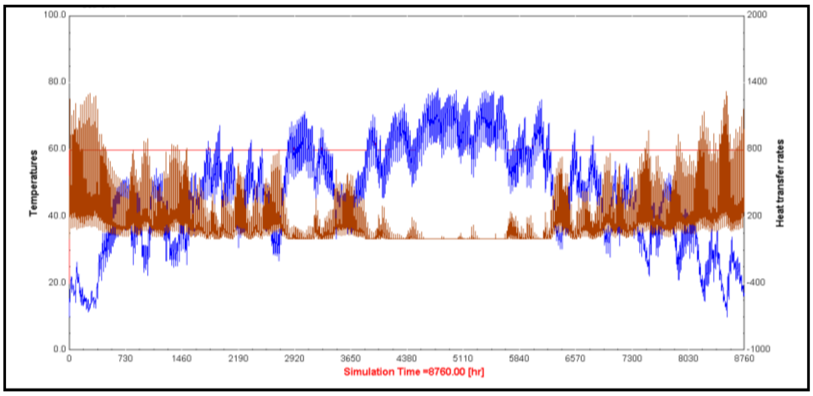


Figure 4. Outputs TRNSYS DHW model. Curves: Set point (red), Outlet temperature (blue), Auxiliary Energy (Brown)

All the demand (heating and DHW) is integrated into one model, as shown in Fig. 5, in order to calculate the dynamical behavior of the system without BTES. In order to accomplish this, it adds a heating circuit to the DHW model and sizes the components according to the design. In the sequel it describes some new components in the model.

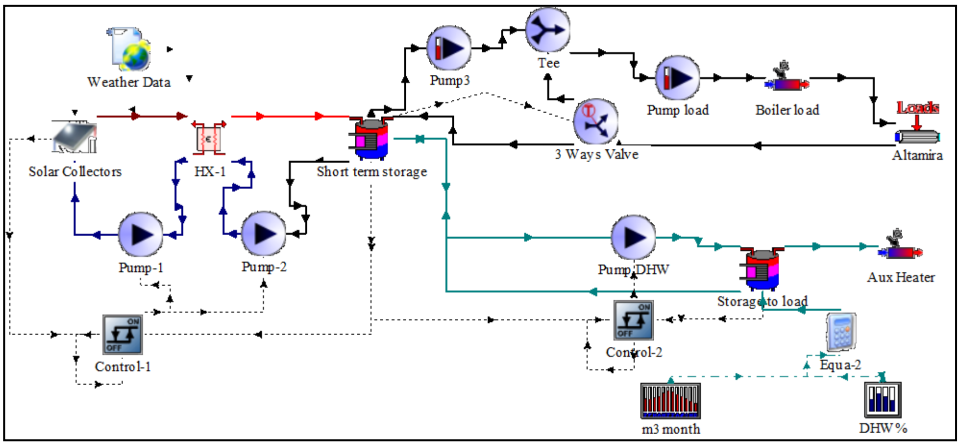


Figure 5. TRNSYS Heating and DHW model integrated

Simulations of the model give us the result shown in Tab. 5. From this table it can see the maximum solar fraction that it can expect from our system without BTES.

Table 5. Outputs data Heating and DHW model

Parameter	Heating	DHW	Total
Demand (MWh)	14.755	3.713	18.468
Auxiliary conventional energy (MWh)	11.363	1.339	12.702
Auxiliary Energy to the fluid (MWh)	9.090	1.071	10.162
Solar Energy (MWh)	5.665	2.554	8.219
Solar Fraction	38%	69%	45%
Performance collector (kWh/m2.a)			627

It proceeds to add the BTES model in the heating and DHW integrated model described above in order to analyses the whole system. Figure 6 shows the final BTES TRNSYS model where it can see the heating and DHW connected with the solar collectors and BTES circuit through the short term storage.

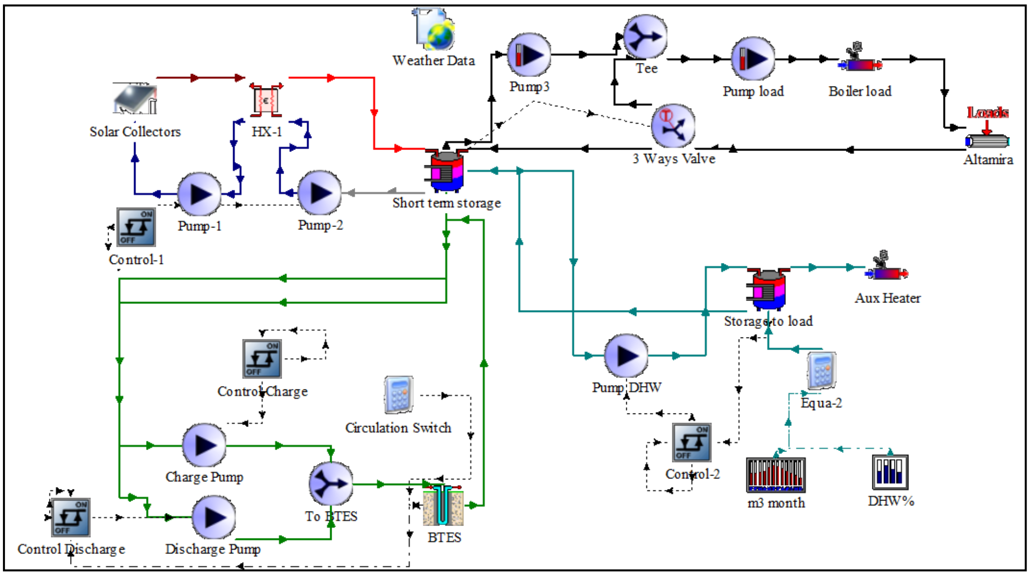


Figure 6. TRNSYS BTES model

3.3 ANALYSIS OF BEHAVIOR OF A BTES FOR SOLAR THERMAL ENERGY

Taking into account the values calculated previously for the sizing of the different components, it proceed to simulate our model to know its dynamical behavior, varying some parameters in order to know their influence in the performance in the system.

3.3.1 SOLAR FRACTION (SF) RESPECT TO FLOW RATE RATIO

Previously it calculate the maximum flow rate required for charge and discharge of the BTES, but as stated previously, these values should be variable. However, as it uses a constant flow rate pump, it can determine the optimum constant flow rate for our case study through simulations. Figure 7 shows the results of those simulations.
From the Fig. 7, it can see that the value of the solar fraction increases with decreasing of the flow rate. In addition, it can see that the SF between years 2 and 3 is greater for lower flow rate. On the other hand, Fig. 8A and 8B show the dynamical behavior of the BTES for flow rate ratios of 1 and 0.15, respectively.

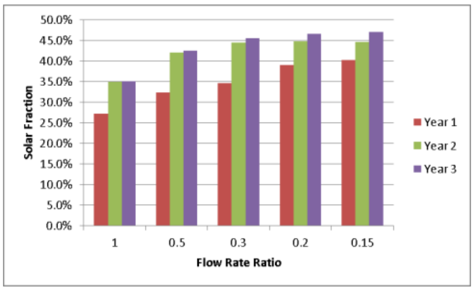
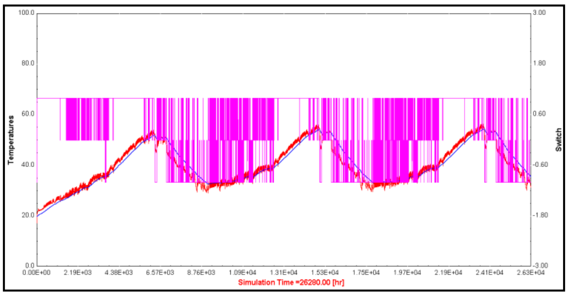


Figure 7. Solar Fraction behavior respect to flow rate

A



B

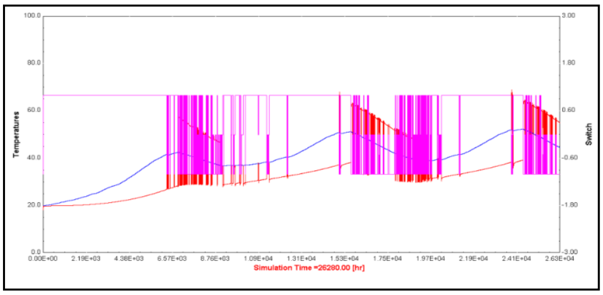
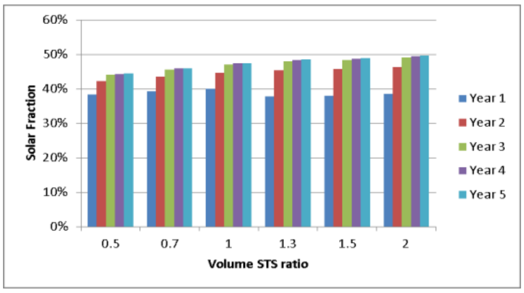


Figure 8. Dynamical behavior of the BTES with flow rate ratio of: A) 1 and B) 0.15. Curves: Average temperature of the BTES (Blue), Output temperature of the BTES (Red), Mode switch function Charge-Discharge (Violet)

3.3.2 SOLAR FRACTION RESPECT TO VOLUME SHORT TERM STORAGE (STS) AND THE NUMBER OF BOREHOLES

Figure 9A shows the results of simulations of the BTES TRNSYS model with varying volume (STS). As it can see in the figure, there is not a strong influence of the volume of the short term storage in the solar fraction, so this result can be taken into account from the economical point of view. On the other hand, Fig. 9B shows the results of the simulations with varying the number of boreholes. As it can see, from 400 boreholes there is not much difference in the increasing of solar fraction, so it can assume this value as optimum.

A



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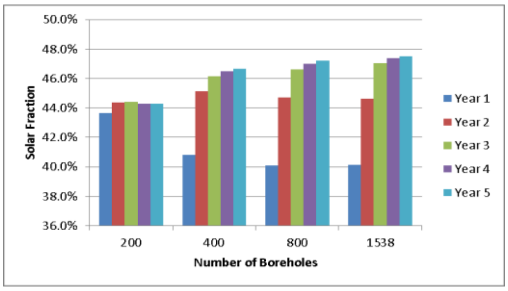

Figure 9. Solar fraction respect to A) Volume STS ratio and B) Number of Boreholes

From the Fig. 9B, it can see that in the case of 200 boreholes, there is not increasing of solar fraction through the years, instead, it can decrease. This is because besides the decreasing of boreholes, there is a decreasing of volume so that is not enough to store the surplus energy.

4. RESULTS

After performing the simulations summarized before, it can estimate an optimum BTES system according to the data. It will be exposed the best results obtained for the Altamira project.

4.1 TRNSYS MODEL PERFORMANCE

Figure 10 shows results of the simulations of BTES system with 400 boreholes by decreasing the flow rate even further. As it can see, a flow rate of 10% of the maximum value calculated previously, is the optimum constant flow rate for our conditions.
After the analysis of dynamical behavior of the BTES system, it can estimate the best configuration according to the performed simulations. Figure 11 shows the data configuration BTES data for the case study. With this configuration it gets 47% of the solar fraction in 5 years with a yield collector of 44%.

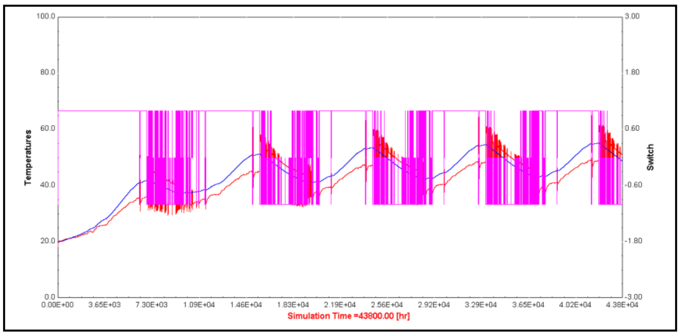

Figure 10. Dynamical behavior of the BTES for the case of study Altamira. Curves: Average temperature of the BTES (Blue), Output temperature of the BTES (Red), Mode switch function Charge-Discharge (Violet)

A

Parameters	Value
Area Solar collector (m^2)	13251
Short term Storage (m^3)	1921
Number of BTES	400
Soil Volume BTES estimated (m^3)	300000
Volume calculated for TRNSYS (m^3)	263407
Distance between Boreholes (m)	3.9
Borehole depth (m)	50
Flow rate charge (m^3/hr)	13
Flow rate discharge (m^3/hr)	18

B

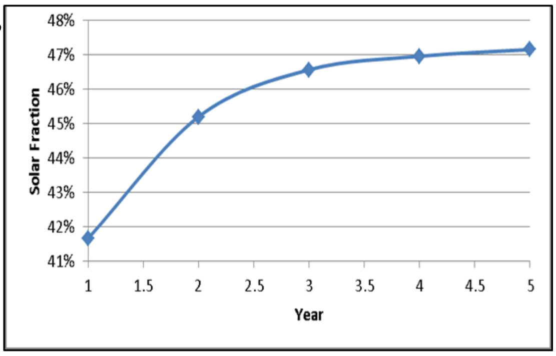

Figure 11. BTES configuration (A) and Solar Fraction (B) for case of study Altamira

4.2 COMPARISON WITH OTHER BTES PROJECTS

The results of the simulations for Altamira and some BTES projects data are recorded in Tab. 6. It can compare the projects respect to different ratios shown in the three last columns. The first of this column describe the ratio of solar energy in MWh delivery for the solar collectors with efficiency of 100 % with respect to heating demand. In other words, this is the ratio of the amount of solar collectors required for the heating demand. The second column shows the volume of BTES in m^3 respect to the heating demand in MWh. Finally, the third one expresses the ratio between volume and solar collector in m^3 with respect to the heating demand in MWh. Finally, the third one expresses the ratio between volume and solar collector is m^3/ m^2. Figure 12 shows in a graphic way the relations mentioned above.

Table 6. Comparison with other BTES projects

Project	had(1) (MWh)	SCA(2) (m^2)	SF(3)	V_{BTES}(4) (m^3)	LSR(5) ($MWh/m^2.a$)	$\frac{LSR*SCA}{HD}$	$\frac{V_{BTES}}{HD}$	$\frac{V_{BTES}}{SCA}$
Altamira Project	18.515	1.3251	48%	263407	1,807	1,3	14,2	19,9
Neckarsulm, DE	16.63	5.000	50%	63400	1,330	4,0	38,1	12,7
Anneberg, SE	1.080	3.000	60%	60000	1,210	3,4	55,6	20,0
Okotoks, CA	720	2.293	90%	35000	1,606	5,1	48,6	15,3

(1) HD: Total heating demand; (2)SCA: Solar collector Area; (3)SF: Solar Fraction; (4)V_{BTES}: Volume of BTES; (5)LSR: local annual solar Radiation

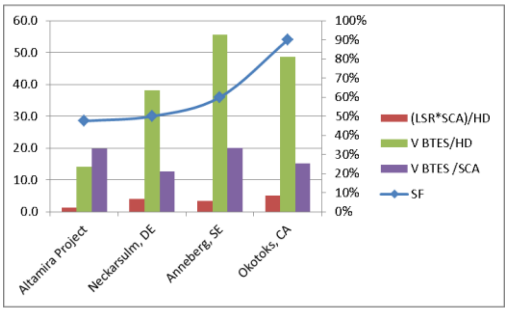

Figure 12. Comparison between BTES projects

Comparing Altamira project and Neckarsulm, it can see that, in order to obtain almost the same solar fraction, less solar collector area and less BTES volume would be required with respect to the heating demand according to the ratios shown in the Tab. 6. From the results it can bear out that Madrid is an interesting place to develop this kind of project.

5. CONCLUSIONS

A TRNSYS model for analysis of dynamical behavior of borehole thermal energy storage (BTES) has been developed by the integration of the several subsystems namely: Solar Collectors, DHW, Heating, BTES and short term storage for Altamira project Case. The simulations showed that the number of boreholes required is 25 % of the value calculated by the energy balance. In turn, the charge and discharge flow rate of the BTES is around 15% of the value calculated to get the expected solar fraction. The volume of short term storage improves just about 2% in solar fraction when its size is duplicated, so the results showed very slight influence in the solar fraction. In this sense, the analysis of dynamical behavior of this kind of systems seems to be necessary to design and avoid oversizing.

This project is relevant for the study of BTES systems in Spain as well as for comparing with other BTES projects. In future research, improvement of this model must be carried out taking into account different issues, such as control strategies and the study of geological parameters. In addition, experimental data are required to verify the BTES TRNSYS model.

6. ACKNOWLEDGEMENTS

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