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The TESSAS Project in Mol: High Temperature Thermal Energy Storage in Saturated Sand Layers with Vertical Heat Exchangers

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ABSTRACT

TESSAS is a European project within the 5th framework program with three partners: Vito – Belgium, IF Technology – the Netherlands and ZAE – Germany. The main goal of this project was to demonstrate and evaluate an underground storage system in a water saturated sand layer for storing high temperature heat. The TESSAS-installation went in operation in May 2002. It concerns a high temperature borehole storage system that stores waste heat at 90°C from a power plant during summer time. During the heating season, the stored heat is discharged and used directly for heating a building of 3.700 m^2 floor area. A maximum temperature of 70°C was reached in the underground by September, the temperature dropped to 30°C at the end of the heating season. The borehole field is built up of 144 vertical heat exchangers (single U-tubes) at a depth of 30m in order to create a storage volume of approximately 16.000 m^3. This is the thermal equivalent of a water storage of ten million liter. This system creates many opportunities in combination with solar collector systems, cogeneration or waste heat (power plants, industrial heat residues,…), not only from a technical and ecological standpoint but also from a economical point of view.

1. INTRODUCTION

When thermal energy supply and demand are not balanced, storage is necessary. For long-term storage of a high quantity of thermal energy (MWhs – GWhs), ATES (Aquifer Thermal Energy Storage) or BTES (Borehole Thermal Energy Storage) will be the most favorable techniques.

An ATES system uses groundwater as a heat transfer medium to bring heat or cold into the underground. A BTES system uses vertical heat exchangers in order to heat up or cool down the sediments. An ATES system can only be installed if the geohydrological parameters at the desired location are appropriate. A BTES system is less influenced by the specific location; although certain rules have to be complied with, the conditions are less stringent. The main difference with most of the know installed storage systems all over the world regards the aim of this project to store heat on a high temperature level. This requires specific care, an ATES system is less evident for this purpose due to possible shaling and clogging problems. This gives another important reason to install a BTES system.

Over the years, several demonstration installations have been built in Europe for the storage of thermal solar energy, the so-called CSHPSS-projects (Central Solar Heating Plants with Seasonal Storage). In these projects, different circumstances were examined such as type of heat exchanger (single-U ; double-U ; co-axial), subsurface (clay, gravel, rock, …), depth (from 6 m to 65 m), number of boreholes (from 7 to 360), temperature (from 50 to 82°C),... The main difference with the TESSAS project regards the type of underground. A storage in water saturated sand hasn't been developed yet. Design and construction of a BTES system will be very different compared to clay or rock formations.

2. HYDROGEOLOGICAL AND THERMAL CHARACTERISTICS OF THE UNDERGROUND

2.1 Geology

The Mol site is located at 26 m above sea level, the U-tube length of 30 m which forms the vertical heat exchanger is placed from 25 m ab.s.l. to -4 m u.s.l. and passes two sedimentary formations:

The Mol formation in the upper part consists in a 18 m Pleistocene well sorted fine sand (quarts) with a silt content of 4%, covered by 2 m of loamy overburden.

The underlying Pliocene Kasterlee formation of 12 m is divided in three sub formations:

- The upper Kasterlee formation (7 m thickness) consists likewise of fine sand, but with a silt/clay content of 11% and a (with depth rising) content of glauconite, which tends from 1% to 24%.

- The middle Kasterlee formation (4 m) averages 24% silt/clay and 25% glauconite.

- The lower part (about 1 m) is situated under the tubes and consists of a silt with fine sand. It contains a silt/clay content > 65%.

Underlying starts the over 90 m thick Miocene Diest formation of fine and middle sands, containing glauconite. The uppermost part contains 7% silt.

2.2 Hydrogeology

Locally the Mol formation and the Kasterlee formation are jointly used by an unconfined aquifer, which is sealed by the lower Kasterlee formation. The average groundwater level is at 23,35 m ab.s.l. (2.65 m below surface) and varies seasonally from 23,5 (February) to 23,15 m ab.s.l. (September), regionally the variation is stronger (2 m). The hydraulic conductivity of the Mol formation averages 2 E-4 m/s, in the upper Kasterlee formation it decreases to 4 E-5 m/s. In the Miocene sediments a huge regional aquifer is located, which locally averages in the upper Diest formation a hydraulic conductivity of 1,6 E-4 m/s and is disconnected hydraulically (semi confined) by the lower Kasterlee formation. The following groundwater velocities result from a maximum hydraulic gradient of 1‰ : Mol formation 6,3 m/year, upper Kasterlee formation 1,3 m/year, upper Diest formation 5 m/year.

2.3 Thermal Response Test

The main thermal characteristics of the underground concern the thermal conductivity (expressed in W/(mK)), the thermal capacity (MJ/(m^3K)) and the borehole resistance (K/(W/m)). There is much uncertainty about the thermal properties of the underground. In literature, many different values are stated for similar sediments. This results in a wide range inside which a choice has to be made. The thermal conductivity of a water saturated sand soil (typical at the TESSAS location in Mol) can be situated between 1,7 and 5 W/(mK). A recommended value can be determined at about 2,5 W/(mK). This value need to be handled with great care, important deviations on this indication value are locally possible due to high groundwater flow or specific granulometric or lithological differences.

One way of measuring the thermal conductivity concerns a lab test. A sample is examined on heat transfer in a lab environment. Although the measuring techniques are reliable, the disadvantage of this test regards the (nearly) impossibility to imitate the real situation. Aspects as ground water level, ground water flow, temperature evolution of the environment, convection flow,… aren't taken into account. The best way of measuring the conductivity is by performing an in-situ test on the heat exchanger itself. In this test a closed circuit is created with a vertical heat exchanger and a water heater. A constant heat is dissipated to the ground and the evolution of the water temperatures makes it possible to calculate for the conductivity.

The performance of an in-situ thermal response test (TRT) also allows to evaluate the borehole resistance. Therefore, three vertical heat exchangers with three different fillings were placed. The suggested fillings were the sand of Mol, a calibrated sand mixture and a bentonite mixture. The first filling is the original present white sand (Mol), from the second filling was expected to give a better packing and therefore lower borehole resistance. The bentonite mixture was used as an experiment on this site, this material is traditionally used for filling. It was not expected that this material would deliver the best results in a water saturated underground such as is the case at the storage site, but it can provide good results in limiting the buoyancy effect (raise of heat in the borehole due to an induced convective flow).

The conductivity measurement is performed with the help of an apparatus based on a heat pump as heat source (figure 1). A constant heat is dissipated in the underground. Therefore a constant flow and a constant temperature difference were established. The absolute temperature of the supply and return water did rise during the test period due to the warming up of the soil. The heat pump was placed as close as possible to the vertical heat exchanger, all the connection pipes need to be well insulated. The distance between the installed vertical heat exchangers is 4 m. The measurements were performed for one borehole at a time for a period of 3 to 4 days for each borehole, during this time the temperature of the circulation medium rose from +12.5°C (at the start of the experiment) to ± 30°C. A cooling down period of half a day was integrated after each measuring period.

Figure 1: Mobile TRT test rig with heat pump

The tests on the both sand filled systems delivered excellent results. Due to a high borehole resistance of the bentonite filled borehole, the experiment was ended after only 66 hours. The supply water temperature exceeded 45°C, which stopped the heat pump.

The results were calculated by means of a two dimensional finite volume model (Yavuzturt et al 1999, Austin et al 2000). This model uses a Nelder-Mead algorithm to determine the heat conductivity of the soil and the borehole resistance. This is an overview of the results:

Table 1: Results of the conductivity measurements

Borehole filling	HEAT CONDUCTIVITY COEFFICIENT [W/(M.K)]	
	Soil	Borehole
Mol sand	2,47 ± 0,02	2,6 ± 0,5
Calibrated sand	2,40 ± 0,02	1,3 ± 0,5
Bentonite mixture	1,86 ± 0,02	2,2 ± 0,5

The deviation of the heat conductivity coefficient of the soil measured in the borehole with a bentonite filling is one of the most surprising results. Theoretically, all these coefficients should be equal. The deflection can be explained by the premature ending of the measurement on the bentonite borehole; the measured curve was not stabilized at that time. Conclusion: the heat conductivity coefficient of the soil is about 2,45 W/(mK). The Mol sand gives the best results as to the borehole resistance, no extra costs must be made as to the application of other fillings.

3. SYSTEM SIMULATION

3.1 TRNSYS model

In order to predict the behaviour and the performance of the underground thermal energy storage, a simulation model can be set up. The two most important tasks in borehole thermal energy storage modelling are the pre-design of the borehole configuration and the detailed simulation of the heat balance (system interaction). The difficulty lies in the numerical representation of the complex geometry of multi-borehole installations and the interaction between the convective heat transport and the conductive process in the surrounding ground. The following thermal processes need to be considered: heat conduction in the ground, thermal interaction between different boreholes, regional groundwater flow and natural convection induced by temperature dependent density differences. TRNSYS is a very powerful software tool, designed to simulate the transient performance of thermal energy systems. TRNSYS relies on a modular approach to solve large systems of equations described by Fortran subroutines. By connecting different modules to each other, simulations of complex energy systems can be done. Specific modules for energy storage systems were developed / adapted in order to be compatible with TRNSYS. At the moment, these models are the best available simulation tools for this purpose. The models are also validated by measuring data on similar projects, yet specific differences in this project will lead to new model corrections.

For modelling of the TESSAS pilot storage the regular DST-Model (Duct Ground Heat Storage Model) from D.Pahud was used with input data from the thermal response tests carried out. In a second step the impact of groundwater flow was considered in the same way as done in the DSTP-Model. Thus monitoring data of the storage can validate the modified simulation model.

Within initial investigations the heating system was modelled in TRNSYS. The system comprises two circuits, the primary and the secondary one. In the primary loop a variable energy rate (Q_{Aux}) is added to the cold return water from the heat exchanger in order to provide a constant supply flow temperature of 95 °C. The flow rate of the temperature controlled pump P1 can be varied from 3 to 14 m³/h in order to limit the supply flow temperature of the secondary loop to its required value. The flow rate of the secondary loop is constant at 14 m³/h. The heated fluid is supplied from the outlet of the heat exchanger to the thermal load (building). In order to shift the profile of the heating demand, the system is connected to an experimental duct storage. By means of two 3-way valves (V1 and V2) the storage can be operated in different operational modes. The hydraulics of the Tessas system is modelled in TRNSYS according to the hydraulics scheme on figure 2.

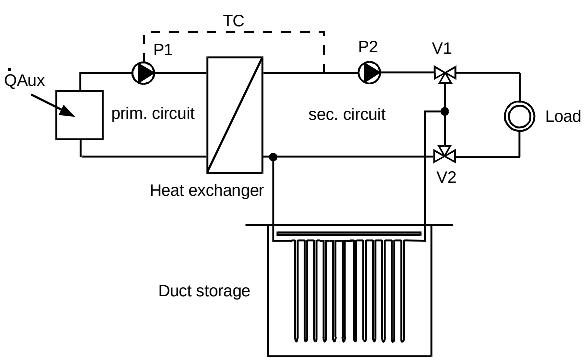

Figure 2: Hydraulic scheme – TRNSYS model

3.2 Simulation results

At first, a control strategy had to be considered. Since unlimited heat can be supplied in this TESSAS-project, different strategies can be used. A possible application of this technique in the future will be cogeneration (Combined Heat and Power generation or CHP) coupled energy storage, the strategy has to comply with this application. It's possible to charge at full power in severe winter conditions; this is, however, not very logical. In real conditions, during that time all the produced heat will be used to cover the heat demand (if using a CHP). Therefore, it will be necessary to limit the total heat supply. In order to determine the level of heat limitation, the power (that would be installed in our building if we would use a CHP) was calculated. The CHP was determined on 170 kW_t. This lead to the control strategy, where charging will only be possible if the temperature difference between room temperature and outside temperature is less then 10 K. Since the building load is assumed to be 17 kW/K, this comes to a thermal power of 170 kW. The results show realistic figures. The charging power will alter in relation to the outside temperature. Yet, restricted charging is still possible in winter time, e.g. during night time / weekends but the overall trend is still a seasonal storage.

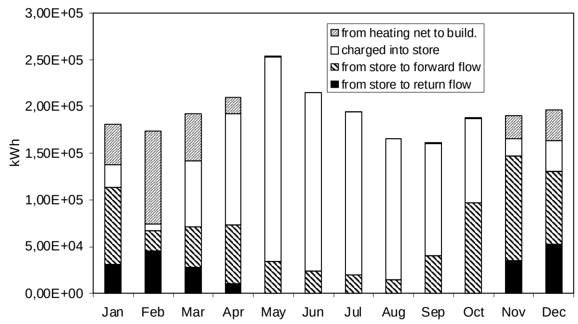

Figure 3: Monthly Energy Balance (Store 29.550 m^2, B=2,5 m) – control strategy

The results shown in figure 3 are the outcome of steady state conditions. The first years of operation can be significantly different compared to long term. Since the TESSAS-project has an operation period of about two years, the results after the first and the second year are the most important. Attention was also given to the borehole distance.

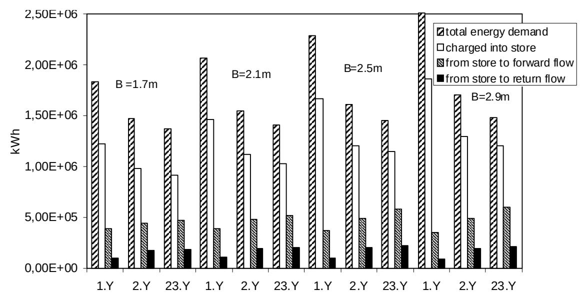

Figure 4: Annual energy flows of 1st, 2nd and 23rd year of operation (B = 1,7 … 2,9 m, 2-U)

Both items are visualised in figure 4. This graph shows that a good compromise can be found with a borehole distance of about 2 m. In the first year, the total discharged heat is at its maximum when using a borehole distance of 2 m. After two years, the additional heat delivered by the district heating amounts to only 39 % when using a 2m distance, against 44 % at 1.7 m. For larger stores (2.5 to 2.9 m distance), the gain is minimal (still 37 % additional heating). Another reason for choosing a smaller storage system, is the necessary total heat supply, which is at its maximum during the first year. This is limited to 2 GWh by using a 2 m distance, against 2.5 GWh at 2.9 m. Further, the storage temperatures are higher at smaller borehole distances (max. 80° C (2 m); 70° C (2,9 m)).

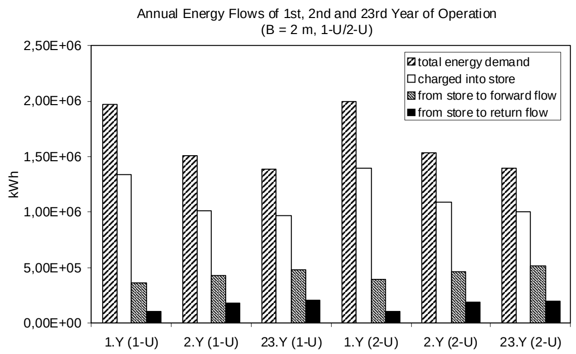

Figure 5: Annual energy flows of 1st, 2nd and 23rd Year of operation (B = 2 m, 1-U/2-U)

The choice between the use of a 1-U or a 2-U vertical heat exchanger could be made on the basis of figure 5. The differences are minor (2-U gives 7.5 % more discharging during the first year, less then 4 % more discharging in a steady state). On the other hand, the material cost for a 2-U doubles compared to 1-U. Because of this, the choice of 1-U is made.

An overview of the calculated thermal losses is given in figure 6. With forced convection (calculated with the actual groundwater flow of 12 m/year) the losses are expected to be about 4 % higher compared to no groundwater flow.

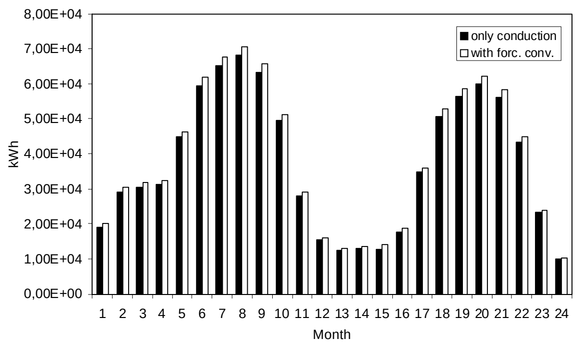

Figure 6: Storage thermal losses during initial 24 months of operation

4. BOREHOLE STORAGE SYSTEM

4.1 Borehole configuration

The vertical heat exchangers are positioned in a hexagonal shape with a distance between them of 2 meters (figure 7). On a total of 144 boreholes with a borehole distance of 2 m, the storage diameter is 26 m. Due to the homogeneous sand layer 0–30 m below ground level, hence the storage depth is based on 30 m and the depth/diameter-ratio is close to 1. The storage area is divided in four sections of 12 circuits each. Each circuit is composed of three boreholes in series, connected (during loading mode) to a centrally placed supply collector and an outside placed return collector.

In order to create a 3-D profile of the storage temperatures, it is necessary to place 66 temperature sensors at different places on various depths. For this purpose, 3-wire Pt-100 sensors are placed up to 41 meters below ground level in the saturated Mol-sand. They are placed in the measurement boreholes M1…12 (figure 7).

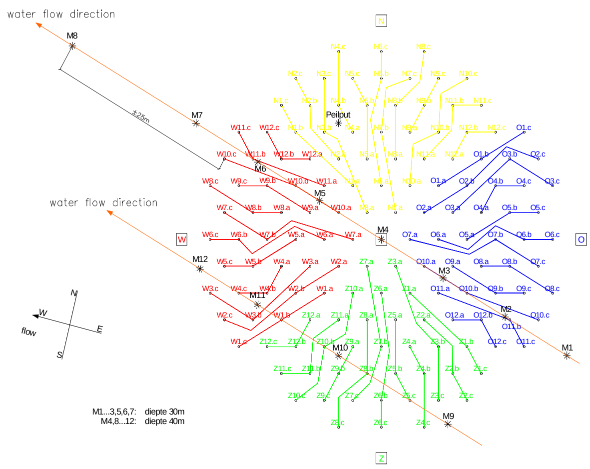

Figure 7: Borehole configuration : vertical heat exchangers + measurement boreholes (M1…12)

4.2 Construction of the borehole system

The construction works started with the outside part. One meter of ground was excavated in order to create a buffer zone (with ground and insulation) from the top of the storage field to the ambient. The drilling pattern was then indicated on the field by Vito according to the design. The drilling of the boreholes had to be planned carefully. The insertion of the heat exchangers (figure 8) must take place immediately after the removal of the drilling machine.

Figure 8: Single-U vertical heat exchanger

The temperature sensors were placed around a PVC-pipe at different distances. This made it possible to bring the sensors in the underground at a particular depth. In three weeks time, all the drilling work was completed successfully (average of 7 boreholes a day). Afterwards, the vertical heat exchangers (VHE) were connected in 48 circuits of 3 VHE's in series (figure 9). The 5 collector casings were brought on place and the manifolds were installed inside.

Figure 9: Storage field, hydraulic connection vertical heat exchangers (3 in series)

Afterwards the different circuits were connected. The connections were all made with electrical socket welds. At the end, the supply pipes were installed. The next step involved the equalisation of the ground surface with a small slope from the centre to the edge of the storage field. Afterwards the insulation material was installed. In total 20 cm (2 x 10 cm placed crosswise) of XPS (extruded polystyrene) with a surface of 900 m^2 was put on top of the storage field and around the collector casings (figure 10).

Figure 10: Insulation layer (2 x 10 cm XPS) on top of the storage field

The insulation plates were covered with a PE (polyethylene) foil. Finally, it was covered with ground and plants. The temperature sensors were placed in watertight casings above the ground level, those were connected to temperature transmitters which at their turn were connected to the data loggers in the central pit.

5. MONITORING PROGRAM

An intensive monitoring program was set up in order to evaluate the system performance. The program consists of two main items : the analysis of the ground temperatures (heat transfer in the underground) and an energy transfer and temperature analysis of the different hydraulic circuits (storage field to building system ; district heating to storage field and district heating to building system).

5.1 Charging process

On April 24, 2002 the Tessas process was brought in operation. During the first five months an intensive charging process took place, 900 MWh of heat was brought in the underground storage field (16.000 m^3). In the beginning, it was possible to reach a charging power of 450 kW due to the high temperature difference between the supplied temperature (90°C) from the district heating (power plant) and the undisturbed ground temperature (12°C). This power decreases to 240 kW at the end of September when the storage reached the highest average temperature.

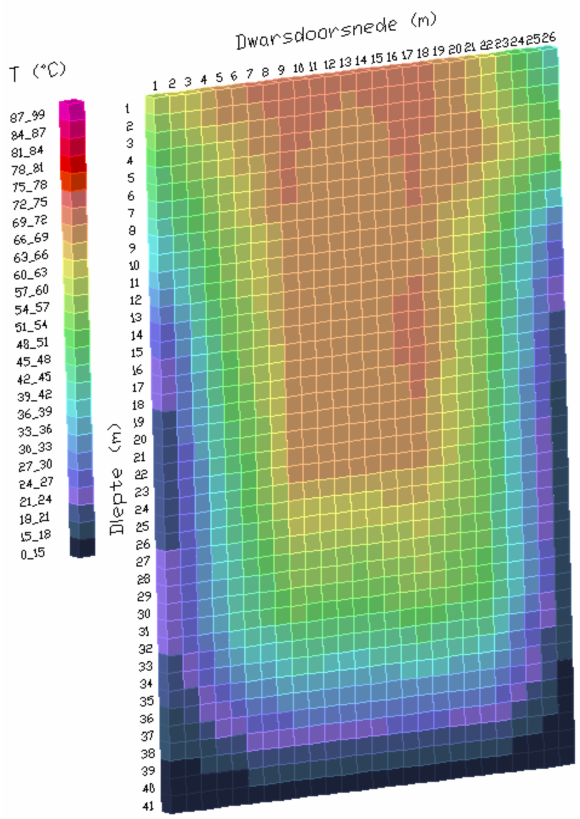

Figure 11: Temperature profile in underground borehole storage field (cross section through storage center)

On September 26, the maximum storage temperature was reached. At that time, the average storage temperature was 54,3°C with a maximum of 71°C at a depth of 1,5 m below the ground surface. In order to measure the average storage temperature the storage field is divided in parts of 1 m^3. Several temperature sensors are located on different places and at different depths, a temperature value can be given at each m^3 storage volume by interpolation between the measuring points. A simulation view at the end of September (maximum storage temperatures) over the cross section of the storage field is shown in figure 11. The vertical heat exchangers are positioned in a hexagonal shape with a distance between them of 2 meters (figure 7).

Figure 12 shows the monthly charged energy and loading hours. During the first year op operation (April 2002 – March 2003) a total energy amount of 1065 MWh is stored, the second year only 710 MWh was needed in order to become almost the same average storage temperature.

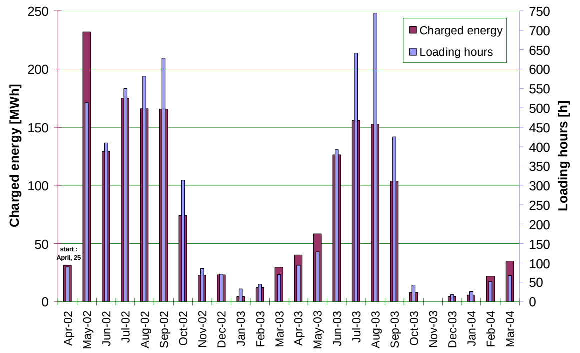

Figure 12: Monthly values of charged energy [MWh] and charging hours [h]

As a conclusion can be stated that the charging process went significant better then foreseen in the computer simulations with the TRNSYS model.

5.2 Discharging process

According to the control strategy, the unloading process could take place every time the return temperature of the building heating circuit is lower then the supply temperature from the storage field. Two cases are possible, or the heat is completely supplied by the storage system (this is indicated as a direct unloading cycle) or the storage system only delivers part of the heat demand (this is called indirect unloading cycle). In the second case, the district heating supplies the additional heat.

During the first discharging period (heating season 2002 – 2003) a rather limited energy amount could be recuperated form the storage field. From the first of October until the end of November only 325 hours of unloading occurred (22% of total time). In December this percentage even went further down to 3%. The average unloading power drops from 56 kW in September to 33 kW in November.

There were some reasons for this low utilization of the stored heat. Main reason concerns the existing heating system of the building, were the storage system is coupled with. This heating system exists of convector elements. In order to get enough heat supply to the building, this system requires a high supply temperature. An optimization of the weather dependant control system was made in advance but it's clear that this wasn't enough to cope with this problem. Additional the return temperature of this heating system is much too high. The average return temperature increases from 50°C at the beginning of November to 60°C at the beginning of January. The combination of a high supply temperature and a low temperature difference results in a high return temperature of the building system which is pernicious for the uncharging process of the storage.

A drastic change of the TESSAS control strategy was necessary in order to be able to recuperate the stored heat. From October on, the control strategy became rather simple because all is focused now on the unloading process. During the morning (from 6 to 10 a.m.) the building is heated by the district heating system. The TESSAS-system stays out of operation. For the rest of the day (office hours as well as during night) there is a direct unloading of the store (as long as the outside temperature is not below 2°C because of safety reasons of some cooling batteries). During that time, the district heating isn't functioning. This strategy was a success as the periods with high heat demand (each morning) were completely covered with the district heating system. For the rest of the day and during night the storage system was able to provide enough energy for maintaining the required temperature level in the building.

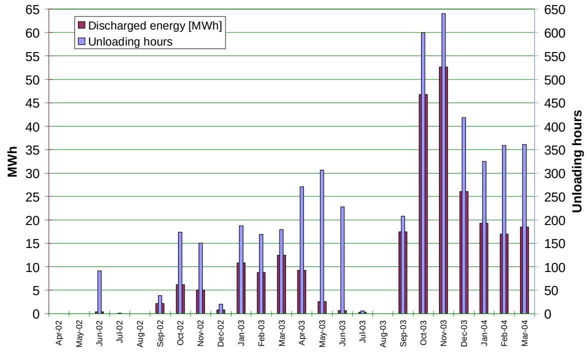

Figure 13: Monthly values of discharged energy [MWh] and discharging hours [h]

Due to the described adaptations to the control strategy, a significant improvement of the discharging process was obtained. This is visualized in figure 13. During the second year of operation (April 03 – march 04) in total 211 MWh of heat was transferred from the storage field to the building. In the first year only 47 MWh of energy was discharged. The storage efficiency (defined as the simple calculation of ratio input versus output of thermal energy) is thereby brought to almost 30 %; due to the fact that steady state is not yet reached, there is still room for further efficiency improvement as the storage edges are not yet heated up properly. The discharging process evaluated with an average of 80 kWt during the first two months (sept / oct). The maximum capacity for this period was about 130 kWt.

An overview of the temperatures at different locations in the field on 16 m depth are shown in figure 14. The exact locations of the sensors M1…M8 is shown in figure 7.

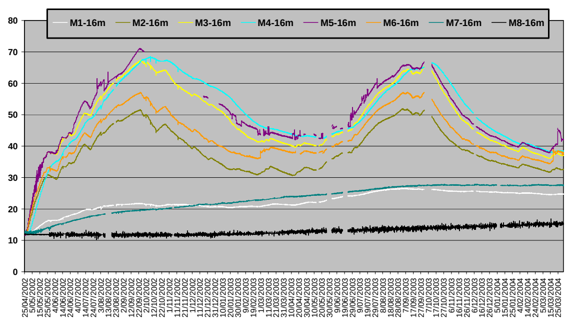

Figure 14: Storage temperatures on 16 m depth at various locations

Within the existing boundary conditions that the building heating system causes important limitations to the discharging process, the discharge evolution is evaluated very promising.

6. EVALUATION

6.1 Simulation validation

As stated before, for system design the TRNSYS DST-model was used. Some input parameters like ground thermal conductivity and borehole resistance were measured by site investigation (thermal response test), others had to be assumed or have changed through the construction and operation phase. Thus the model has to be validated against measured values from the monitoring phase.

A reliable comparison of the simulation model and the real storage has to be based on the measured load profile. The measured flow rate and inlet/outlet temperatures of the storage have been used as input values for the model. Occasional and obvious mistakes due to problems with the data acquisition in the raw data files were corrected.

6.1.1 Comparison of design and measurement

The TRNSYS-DST model with the real design parameters has been used to compare the simulation model and the real storage. The period of investigation starts at 25.04.2002 and runs till 26.11.2003. The total energy balances of measurement and simulation are listed in table 2.

Table 2: Measured and simulated energy balances from 25.04.2002 till 26.11.2003

	Charging	Discharging
	[MWh]	[MWh]
Measurement	1567	179
Simulation	1304	327
Aberration	-17 %	+83 %

The description of the charging process by the simulation model is acceptable, in contrary to the discharging process. While the charged energy in the observed period is 17 % less than measured the discharged energy exceeds the measurement by 83 %.

The dynamics of the storage on a monthly time scale during charging is described quiet well, with an average deviation between simulation and measurement of 23 %. For discharging significant differences between simulation and measurement can be recognized. Although the general dynamical behavior is described by the model the average deviation is 104 %. For discharging the model gives permanently higher values than measured.

Several reasons have to be considered to explain the much lower amount of discharged energy. First of all forced convection, due to the ground water flow through the storage in horizontal direction, could have been underestimated. In this case this effect should be visible in the temperature measurements M1-M12 as a displacement of the isotherms with respect to the storage centre. The second one is a buoyancy flow due to the big temperature differences especially in the first years of operation. Free convection shifts the hot water to the top of the storage and cold water flows back from the side and bottom of the storage. This leads to a faster energy distribution in the ground and therefore to a lower temperature level in the storage. A third reason could be that the thermal conductivity of the ground has been underestimated. Higher conductivity also leads to a faster energy distribution and therefore to a lower temperature level in the storage especially in the starting phase where the surrounding of the storage is heated up. A final reason could be higher losses through the top of the storage. In order to find reasons for these significant differences measured and simulated storage temperatures were compared. The aim is to adapt the model to reality so that a reasonable prognosis of the storage behavior for different boundary conditions is possible.

Two-dimensional temperature diagrams allow the analysis of the responsible effect for the higher losses (figure 15, situation at 25.09.2002). If there is free convection due to temperature differences it should have a maximum around this date. The temperature distribution and the changes of this diagram in time allow the investigation of the effect of forced horizontal convection. The influence of the thermal ground conductivity and the losses through the top of the storage must be analyzed by computer simulation.

In figure 15, a cut through is shown of the storage from measurement point M1 to M8 which shows the first maximum of the average storage temperature at 25.09.02. The black line at r = 12,6 m and h = 31m marks the edges of the storage. The hottest region in the storage gets broader to the top and down to a depth of around 10 m a warm bubble exceeds the edge of the storage till a radius of about 25 m. On the other hand the hottest region does not exceed a depth of about 26 m. As heat conduction propagates spherically this temperature distribution can not be explained by pure heat conduction. The piping at the top of the storage which leads to a bigger energy entry in this region could be a reason but if this would be the dominating effect the temperature there should be significant higher. The conclusion is that there must be buoyancy induced by density differences due to temperature gradient in the ground. This effect enhances the losses of the storage especially at the beginning when the temperature gradient is very steep. Probably at steady state conditions this effect is reduced or can even be neglected.

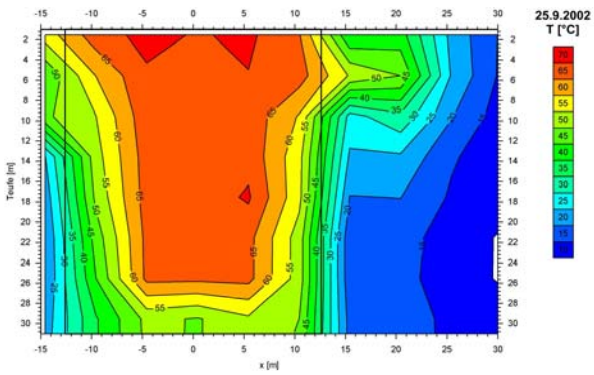

Figure 15: First maximum of average storage temperature at 25.09.2002 (measurement)

Forced convection due to ground water flow can also be identified in this figure. The 65 °C and the 55 °C isotherm are displaced slightly in the order of 1-2 m to the right at a depth from 26m to 9m. In the upper part of the storage the situation is more complicated. Here both effects are superposed so that an explicit conclusion is not possible. As a result a displacement of the isotherms of about 2,4-4,8 m per year in flow direction of the groundwater is observed. This agrees with the results of the geological investigation of the site which predicted a groundwater velocity of less than 6,3 m/year in the Mol sand layer (18m) and 1,3 m/year in the upper Kasterlee formation (7m). In the first layer till a depth of around 3 - 4m a heat flow to the opposite direction is recognized which we can not explain through ground water flow as the average groundwater level is 2,6m below surface.

Besides these convection effects it has to be examined if other effects can also explain the differences between measurement and simulation. The examined storage has a volume of 14963 m³. Assuming no heat losses of the storage and a total charged energy amount of 1388 MWh (charging minus discharging from 25.04.02 till 26.11.03) into this volume with an volumetric heat capacity of 2,5 MJ/m³/K the temperature in the storage would rise 136 K. The measured temperature rise is only about 45 K so we conclude that about two third of the energy has been distributed to the surrounding. In order to validate this rough estimation the measured temperatures (M4, M5, M6, M7, M8 according figure 7) were taken and a temperature profile was drawn up of the storage as a function of the distance from the centre.

Assuming a cylinder symmetrical temperature profile the stored energy can be calculated. Taking the theoretical warmer side of the storage for this calculation an overestimation of the stored energy is expected. The stored energy in an infinite tube with wall thickness *dr* is:

$$dQ = 2 \cdot C_V \cdot H \cdot \pi \int_0^{R_0} \Delta T(r) \cdot r \cdot dr \tag{1}$$

where dQ, C_v, H, $\Delta T(r)$, r, R_o are the stored heat, volumetric heat capacity, depth of storage, temperature difference with undisturbed ground, distance from the center and tube radius, respectively.

The result is faced in figure 16. The energy distribution complies to the first estimation. Only around one third of the energy in the region from 0 m to 30 m below surface is stored within a radius of 12,6 m which is the actual storage radius. Most of the energy within the storage is located in the outer part as the capacity of the storage grows with a power of two with the radius.

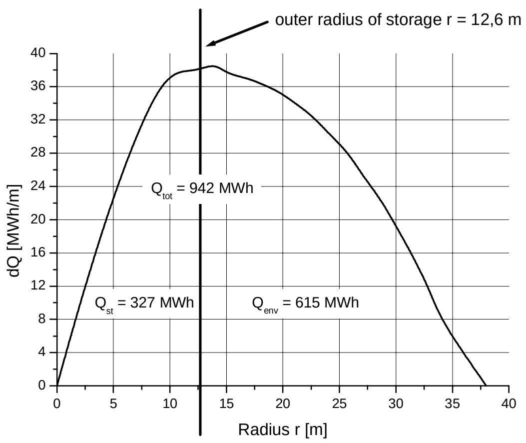

Figure 16: Average energy distribution in the storage and the environment at 26.11.03

The stored energy beneath the storage can also be calculated, it's estimated as approximately 136 MWh. The losses through the top are about 43 MWh which has been calculated with the DST-model. In total the result is an energy amount of 1121 MWh, 267 MWh are still missing. The temperatures in the storage region are known best so that the value for the stored energy in this region should be quite accurate. It is about 24 % or 327 MWh of the loaded energy.

The losses calculated from measured temperatures are higher than the simulated values. These values even underestimate the real losses of the storage, as indicated before, thus it can be concluded that the DST-model underestimates the storage losses for the observed period of time. The fact that the discharged energy in reality is much lower than in the simulation supports this conclusion. In the next step the model is adapted to adjust at least measured and simulated energy balances to each other. This adapted model can then be used to simulate the long term storage behavior for different boundary conditions.

6.1.2 Adaptation of the simulation model

Because of the big differences between the model and the measured data a dynamic fit has been carried out to identify the model parameters. This dynamic identification failed, as the short term dynamical behavior of the model does not comply well with the real storage behavior. The dynamic fit ended up in a mismatch of the energy balances.

A general problem of this procedure was the lack of data available. For a reliable identification of the parameters several charging and discharging cycles of the storage are necessary. The storage at the moment is still in a preheating phase so that not all relevant operational conditions are available in the measured data set. As the energy balances calculated with the design parameters differ significantly from measured values the main model parameters have been adapted so that model and measurement comply for the observed period of time. The identified parameter sets are listed in table 3. The new parameter is the design value multiplied by the concerning factor of each set.

Table 3: Adapted DST-model parameters

Quantity	*Unit*	*Design value*	*Factor Set 1*	*Factor Set 2*	*Factor Set 3*
Conductivity of ground	*W/m/K*	*2,45*	*1,16*	*1,0*	*1,15*
Volumetric heat capacity of the ground	*KJ/m³/K*	*2500*	*1,0*	*1,11*	*0,93*
Conductivity of borehole filling	*W/m/K*	*2,45*	*1,0*	*0,9*	*1,15*
Insulation thickness	*M*	*0,2*	*0,001*	*1,0*	*0,55*
Darcy velocity	*m/s*	*0,12*10 -6*	*10*	*18*	*19*

The energy balances for charging and discharging on a monthly time scale are described best by parameter Set2. Although the adapted model fits well to the measurement on a monthly time scale it could lead to an underestimation of the long term storage performance. The reason is that the effect of free convection (buoyancy flow) may get weaker due to smaller temperature gradients after the preheating phase. Therefore a clear validation of the DST-model is only possible with long term measurements over several storage cycles. The main question is whether geological design parameters describe best the long term behavior of the storage or if parameter adaptations are necessary to simulate such a storage in the water saturated sand. More detailed 3D models are of course available but they are much more complicated to use, they can not simulate the whole heating system like TRNSYS and therefore lead to a much higher effort during the design process. In order to keep system costs low simple design tools are necessary.

6.1.3 Long term performance

A main question of the TESSAS project is the long term performance of the storage for given boundary conditions. Different simulations have been carried out in order to investigate this performance. The first simulations have been made for the load profile of the building. Further more an ideal load has been used to investigate the dependency of the storage efficiency on boundary conditions. Finally ideal boundary conditions have been extracted to get an idea of the maximum storage efficiency. The storage efficiency has been defined as the ratio of discharged to charged energy amount for one year of operation. The efficiency is calculated for a whole charging and discharging cycle from beginning of May to beginning of May of the following year.

The real load profile of the building has been acquired. This load profile including the measured supply and return temperatures at the heat exchanger have been imported into the simulation model so that a forecast of the storage behavior for real operation conditions was possible. The calculations have been carried out with parameter Set2 and the design values. The efficiency of the storage changes very fast during the first 3 years of operation as the underground around the storage has to be heated up. After the first year the storage efficiency is about 15%. After the second year the storage efficiency is already around 36%. The long term storage efficiency is higher than 46%.

The best efficiency of the storage can be achieved for high supply temperatures of the district heating system, a high heat demand of the consumer and a low essential supply temperature of the consumer. To get an idea of the maximum possible efficiency of the storage the system has been simulated for the maximum supply temperature of the district heating of 95 °C, a heat demand of 4000 MWh/a and a supply/return temperature of the consumer of 45/30 °C. The efficiency for these boundaries as a function of operation years is given in figure 17. The simulation has been carried out for the design parameters and the adapted parameter set which should characterize the real storage behavior.

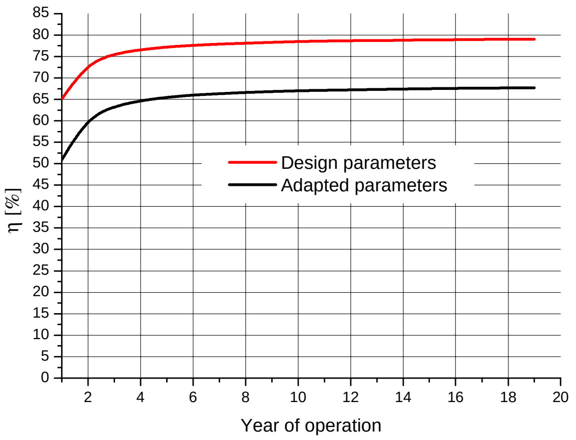

Figure 17: Storage efficiency for ideal boundary conditions

The long term storage efficiency is 67% for the adapted model and 78% for the design parameters. In this case the storage supplies 23% / 24% of the total heat demand.

6.2 Economical evaluation

After the evaluation of the technical performance and characteristics of the TESSAS system, the economical aspects of this system were investigated. The TESSAS project regards a demonstration installation. The investment cost of this specific installation cannot be justified due to the availability of heat (from a coal fired power plant) all year round at an adequately high power level. The main goal of the project concerns a demonstration of a high temperature underground storage field in connection with an office building. Nevertheless, the available information concerning investments and measured energy flows can provide useful information in order to perform an economical evaluation.

As base for comparison of the TESSAS system, a reference installation is defined as a heating system with a gas fired water heater. Table 4 shows the energy flows and performance parameters.

Table 4: Energy flows and performance parameters (steady state + ideal situation)

	TESSAS Steady-state	TESSAS Ideal boundary conditions
REFERENCE INSTALLATION		
GAS	939 MWh	939 MWh
TESSAS		
GAS	479 MWh	200 MWh
ELECTRICITY	14,5 MWh	16 MWh
SPF	28,6	41,6
$\eta_{storage}$	46 %	70 %

Table 5 gives an overview of the comparison of exploitation costs (energy consumption and maintenance) related to the reference situation.

Table 5: Yearly exploitation costs regarding steady state and ideal TESSAS operation

	Steady-state		Ideal boundary conditions	
	reference	TESSAS	reference	TESSAS
Gas	18.778 €	9578 €	18778 €	4000 €
Electricity		745 €		820 €
Maintenance	750 €	250 €	750 €	250 €
TOTAL	19.528 €	10.573 €	19.528 €	5.070 €
Benefit		8.955 €		14.458 €
Cost savings		46 %		74 %

For the installation of the TESSAS installation (storage field, distance piping, connection to existing heating system, ground temperature logging system,…), a total investment of 296.000 € was necessary.

In order to make a realistic cost-benefit-analysis, only strictly necessary costs should be taken into account. The ground temperature logging system exists of 66 sensors, located at 12 different locations on various depths. This investment is very useful for this specific demonstration project in order to evaluate the underground heat transfer but it is not necessary to install these in future storage projects. This investment should be subtracted from the total project cost to obtain a realistic cost analysis. On the other hand, several cost reduction measures can be taken in order to decrease the total project cost. An important item concerns the installation of the vertical heat exchangers (drilling + insertion U-tubes + filling). In this case it represents 50% of the total project (excl temperature logging). Due to the innovative character of the TESSAS installation, only one company made an offer (no competition). The installation of these U-tubes became more and more popular over the past few years with an increasing interest in high performance heat pump systems. Several drilling companies are nowadays specialized in the execution of this kind of work, although a large storage field is still very unusual. A price examination at the market today confirms that rather spectacular price differences can be obtained for future projects. The installation of U-tubes can now be executed at a cost reduced by at least 40%. Furthermore the collector pits (5 pieces which contain the hydraulic circuit collectors) are too expensive and big, they can be replaced by one or two pits with a cheaper construction. Together with other (smaller) cost reduction items, a cost reduction with 27% of total cost without logging is estimated (- 72.000 €).

Table 6 : Profitability overview

Investment cost	
Reference installation	45.000 €
TESSAS installation	194.000 €
Higher investment TESSAS	*149.000 €*
Exploitation cost	
Reference installation	19.528 €
TESSAS installation (steady-state)	10.573 €
TESSAS installation (ideal conditions)	5.070 €
Benefit TESSAS (steady-state)	*8.955 €*
Benefit TESSAS (ideal conditions)	*14.458 €*
Financial figures	
Simple payback time-(steady state)	***16,6 year***
Simple payback time-(ideal cond.)	***10,3 year***

In order to define the profitability of the TESSAS system, a comparison with the reference installation is made. Table 6 gives an overview. The financial figures show simple payback times of 16,6 years (in steady state according the current system operation) and 10,3 years (in ideal boundary conditions). It's important to point out that no financial support is included in this calculation. Due to the high energy saving potential a support of between 15 – 30 % of the investment cost can be expected.

7. CONCLUSIONS

As a conclusion can be stated that the underground storage of high temperature thermal energy provides good perspective for the future. Water saturated sand has excellent heat transfer characteristics which makes it possible to have high thermal power transfer for each meter U-tube in a borehole thermal energy storage system. On the other hand, storing high temperature heat in a saturated sand layer also means high losses due to groundwater and convection flow. An accurate measurement of the thermal conductivity of the underground is important for storage systems on a large scale, safety factors for design can be limited which makes it possible to obtain better economical perspectives. In-situ measurements give additional information on borehole resistance and groundwater flow.

The design of a borehole system can be created with the help of simulations with TRNSYS. The available models have numerous possibilities, but for applications in water saturated sand convection flow can not be included. An important conclusion of the TESSAS project regards the fact that for high temperature applications this convection flow becomes very important. Simulation validation was only possible if some design parameters were adapted rather significant. An additional convection parameter could be of great help. Further research and adaptations to the simulation models regarding convection flow will be work for the future.

Energy storage systems like TESSAS can provide heat directly to the building system. Nevertheless, the importance of low temperature heating systems with high temperature differences can never be pointed out enough. The existing building heating system was indeed an important limiting factor for an efficient discharging process. With ideal boundary conditions, it will be possible to store heat with a yearly storage efficiency of about 70%. These systems provide economical solutions for systems where large amounts of waste heat are available which can not be used directly but can be useful within months. In combination with a cogeneration unit even better economical perspectives are expected as the unit can stay in operation year in year out. Heat excesses can be stored seasonally and will be used in periods with high heat demand.

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