Simulation report
System: ECN TCM model

A Report of IEA Solar Heating and Cooling programme - Task 32
Advanced storage concepts for solar and low energy buildings

Report B6.1 of Subtask B

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Task 32
Storage

SOLAR HEATING & COOLING PROGRAMME
INTERNATIONAL ENERGY AGENCY

IEA Solar Heating and Cooling Programme

The *International Energy Agency* (IEA) is an autonomous body within the framework of the Organization for Economic Co-operation and Development (OECD) based in Paris. Established in 1974 after the first “oil shock,” the IEA is committed to carrying out a comprehensive program of energy cooperation among its members and the Commission of the European Communities.

The IEA provides a legal framework, through IEA Implementing Agreements such as the *Solar Heating and Cooling Agreement*, for international collaboration in energy technology research and development (R&D) and deployment. This IEA experience has proved that such collaboration contributes significantly to faster technological progress, while reducing costs; to eliminating technological risks and duplication of efforts; and to creating numerous other benefits, such as swifter expansion of the knowledge base and easier harmonization of standards.

The *Solar Heating and Cooling Programme* was one of the first IEA Implementing Agreements to be established. Since 1977, its members have been collaborating to advance active solar and passive solar and their application in buildings and other areas, such as agriculture and industry. Current members are:

Australia	Finland	Portugal
Austria	France	Spain
Belgium	Italy	Sweden
Canada	Mexico	Switzerland
Denmark	Netherlands	United States
European Commission	New Zealand	
Germany	Norway	

A total of 39 Tasks have been initiated, 30 of which have been completed. Each Task is managed by an Operating Agent from one of the participating countries. Overall control of the program rests with an Executive Committee comprised of one representative from each contracting party to the Implementing Agreement. In addition to the Task work, a number of special activities—Memorandum of Understanding with solar thermal trade organizations, statistics collection and analysis, conferences and workshops—have been undertaken.

The Tasks of the IEA Solar Heating and Cooling Programme, both underway and completed are as follows:

Current Tasks:

Task 32	*Advanced Storage Concepts for Solar and Low Energy Buildings*
Task 33	*Solar Heat for Industrial Processes*
Task 34	*Testing and Validation of Building Energy Simulation Tools*
Task 35	*PV/Thermal Solar Systems*
Task 36	*Solar Resource Knowledge Management*
Task 37	*Advanced Housing Renovation with Solar & Conservation*
Task 38	*Solar Assisted Cooling Systems*
Task 39	*Polymeric Materials for Solar Thermal Applications*

Completed Tasks:

Task 1	*Investigation of the Performance of Solar Heating and Cooling Systems*
Task 2	*Coordination of Solar Heating and Cooling R&D*
Task 3	*Performance Testing of Solar Collectors*
Task 4	*Development of an Insolation Handbook and Instrument Package*
Task 5	*Use of Existing Meteorological Information for Solar Energy Application*
Task 6	*Performance of Solar Systems Using Evacuated Collectors*
Task 7	*Central Solar Heating Plants with Seasonal Storage*
Task 8	*Passive and Hybrid Solar Low Energy Buildings*
Task 9	*Solar Radiation and Pyranometry Studies*
Task 10	*Solar Materials R&D*
Task 11	*Passive and Hybrid Solar Commercial Buildings*
Task 12	*Building Energy Analysis and Design Tools for Solar Applications*
Task 13	*Advance Solar Low Energy Buildings*
Task 14	*Advance Active Solar Energy Systems*
Task 16	*Photovoltaics in Buildings*
Task 17	*Measuring and Modeling Spectral Radiation*
Task 18	*Advanced Glazing and Associated Materials for Solar and Building Applications*
Task 19	*Solar Air Systems*
Task 20	*Solar Energy in Building Renovation*
Task 21	*Daylight in Buildings*
Task 23	*Optimization of Solar Energy Use in Large Buildings*
Task 22	*Building Energy Analysis Tools*
Task 24	*Solar Procurement*
Task 25	*Solar Assisted Air Conditioning of Buildings*
Task 26	*Solar Combisystems*
Task 28	*Solar Sustainable Housing*
Task 27	*Performance of Solar Facade Components*
Task 29	*Solar Crop Drying*
Task 31	*Daylighting Buildings in the 21st Century*

Completed Working Groups:
CSHPSS, ISOLDE, Materials in Solar Thermal Collectors, and the Evaluation of Task 13 Houses

To find Solar Heating and Cooling Programme publications and learn more about the Programme visit **www.iea-shc.org** or contact the SHC Executive Secretary, Pamela Murphy, e-mail: pmurphy@MorseAssociatesInc.com

September 2007

What is IEA SHC Task 32
"Advanced Storage Concepts for solar and low energy buildings" ?

The main goal of this Task is to investigate new or advanced solutions for storing heat in systems providing heating or cooling for low energy buildings.

- The first objective is to contribute to the development of advanced storage solutions in thermal solar systems for buildings that lead to high solar fraction up to 100% in a typical 45N latitude climate.

- The second objective is to propose advanced storage solutions for other heating or cooling technologies than solar, for example systems based on current compression and absorption heat pumps or new heat pumps based on the storage material itself.

Applications that are included in the scope of this task include:

- new buildings designed for low energy consumption
- buildings retrofitted for low energy consumption.

The ambition of the Task is not to develop new storage systems independent of a system application. The focus is on the integration of advanced storage concepts in a thermal system for low energy housing. This provides both a framework and a goal to develop new technologies.

The Subtasks are:
- Subtask A: Evaluation and Dissemination
- Subtask B: Chemical and Sorption
- Subtask C: Phase Change Materials
- Subtask D: Water tank solutions

Duration
July 2003 - December 2007.
www.iea-shc.org look for Task32

IEA SHC Task 32 Subtask B
"Chemical and Sorption Storage"

This report is part of Subtask B of the Task 32 of the Solar Heating and Cooling Programme of the International Energy Agency dealing with solutions of storage based on adsoprtion or absorption processes and on thermochemical reactions.

This report presents a simulation study on one of the advanced storage concepts that was proposed by a participating team in Task 32.
The concept and the simulation tool have been developped by the participating team. The framework for simulating the solar heating system including the new storage was developped within Task 32.

This joint effort has allowed Task 32 to address several new storage concepts thanks to a common work on different storage technologies but with the same reference system.

The Operating Agent would like to thank the author of this document and his institution for their implication in the search of future storage solutions for solar thermal energy, the key to a solar future for the heating and cooling of our buildings.

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for the Swiss Federal Office of Energy

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Content

1 General description of ECN TCM model

Introduction

The ECN Thermo-Chemical Materials (TCM) heat storage system is an absorption process that is based on the hydration of a solid TCM salt. At this moment, the development of this system is still in a very early stage. The research in this stage focuses on materials characterisation (now mainly on the hydration of $MgSO_4$ powder). The outlook for the future is to develop a seasonal storage system for solar heat with the solid absorption material that will be selected.

Main features

The system is meant for seasonal storage of solar heat for residential applications. The heat is stored by means of the hydration and dehydration of a salt. The selection of the salt is still ongoing.
The charging of the store involves the endothermic dehydration of the salt in the dissociation reactor to a dehydrated salt and to water vapour which is condensed, the condensation energy being rejected to a borehole. There is a net flow of material from the storage vessel for the hydrated salt to the separate vessels for the dehydrated salt and the condensed water (see Figure 1). The discharge of the store, used for space heating and DHW, utilises the exothermic hydration in the association reactor of the salt by water vapour that has been evaporated using heat from the borehole. The TCM storage system thus works as a chemical heat pump, but with a very large internal storage capacity of several GJ. In the discharge phase there is a net flow of material from the separate storage vessels for the water and the dehydrated salt to the store for the hydrated salt. The process thus requires “pumping” of powder between the vessels and the reactors.

Heat management philosophy

The TCM system will be designed for the seasonal storage of solar heat for residential applications. A complete system will consist of a solar thermal collector array (preferably using vacuum tube collectors), a water tank and a TCM storage, as indicated in Figure 1. Since the TCM storage will in practise be limited in power, the water storage provides the high power load, after which the TCM storage can reload the water tank at a lower power level. The system will be controlled in such a way that the solar collector array gives priority to the loading of the water storage. Only when the water storage is fully loaded, the collector array switches to loading the TCM storage, provided that the array can still provide the temperature level required for loading the TCM.
The TCM storage itself consists of a number of components, such as storage tanks for the separate components (hydrated salt, dehydrated salt and water), as well as separate reactors for the hydration and dehydration. Often, solid sorption systems are designed in such a way that the hydration and dehydration reactions take place directly inside a (fixed-bed) TCM storage vessel. However, for large storage systems this is not optimal due to the large thermal capacity of the entire storage vessel, leading to substantial sensible losses at frequent on/off switching. Therefore, in the present design, separate reactors are used for the hydration and dehydration reactions. These reactors contain only a small amount of TCM at one time, thereby allowing much faster on/off switching of the system and strongly reducing these sensible losses. Also, by using separate reactors, many options exist to increase the heat- and vapour transfer by optimised reactor design, as compared to fixed bed systems. However, the use of separate reactors also requires the transport of material between the storage and the reactor, as well as through the reactor, which may be complicated and will use additional parasitic energy.

In the present calculations, a partly idealised model was used, ignoring all problems related to mass transfer and assuming that the TCM system can deliver any power required by the load.

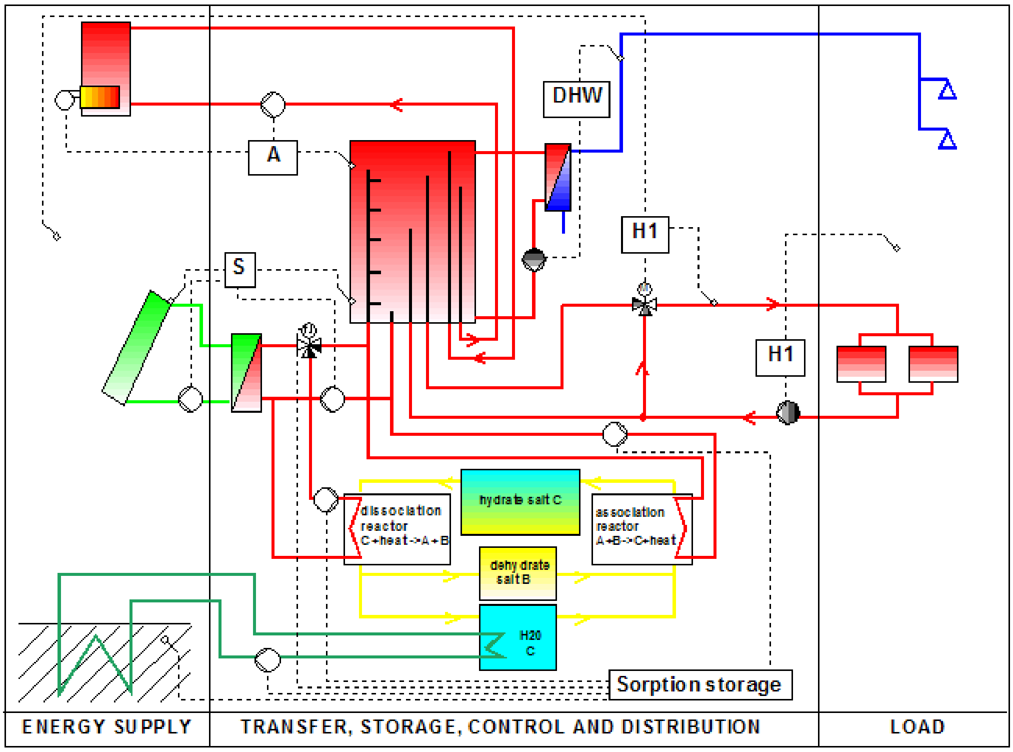

Figure 1: Full system including TCM storage and water tank.

Cost (range)
Not yet applicable

Market distribution
Not yet applicable

2 Modelling of the system

Since the research is still in the phase of materials research, and no (sub)system measurements have been carried out, many critical parameters are at present still unknown. In particular, neither the characteristics of the material still-to-be-selected are known, nor the design of the hydration and dehydration reactors is known, including parameters such as power delivered or parasitic energy use. Therefore, for the first calculations, a basic system was modelled with a storage capacity of 4 to 6 GJ, that can supply any power required and for which all parasitic energy use was ignored.

2.1 TRNSYS model

For IEA SHC Task 32, two sets of calculations were carried out, as shown in Figure 2

1. The first set of calculations was carried out in April 2007, according to the simulation scheme shown in the left part of Figure 2. An ideal borehole was used that could supply an infinite amount of 10 °C water to the TCM evaporator / condenser. DH was assumed to be 61 kJ/mol, resulting in a load temperature a little over 50 °C, T_unload was assumed to be 50 °C, a 4 GJ TCM storage was used and calculations were carried out for a 13 month period. The TCM tank was built into the TRNSYS template by removing

the hot water storage and replacing it with the TCM storage. Several changes were applied to the task 32 template to be able to incorporate the TCM tank instead of the water tank:

- A new collector control was introduced, based on state of charge (SOC) instead of on internal tank temperature
- The TCM storage was charged from SOC=10% to SOC=20% by the auxiliary heater, whenever the SOC dropped below SOC=10%, to limit heater on/off switches. This also required an auxiliary heater control based on the SOC of the TCM tank.
- The template heater was replaced by an ideal heater with an efficiency of 90%, because of problems with the template heater control.

2. The second set of calculations was carried out in January 2008, according to the simulation scheme shown in the right part of Figure 2. In this case, the choice was made not to remove the water tank (as done in the first set of calculations), but to feed the water tank from the TCM storage. Also, instead of the ideal borehole, the TES type 557 borehole model was used (no preheating was applied). This resulted in 3 additional pumps to be applied (between borehole and TCM storage, between vacuum collector array and TCM storage, and between TCM storage and water tank). The control of the pump between collector and water tank was not changed, but whenever the overheat protection of the water storage vessel is on and the SOC of the TCM storage is less than 90%, the pump supplying the collector heat to the TCM storage is switched on, together with the borehole pump to remove the condensation energy. The TCM storage will only load if the temperature is high enough, otherwise the water will simply be circulated through the TCM storage back to the collector, which is not an optimised control for a real system but can be used in the simulation since the sensible heat of the TCM storage is ignored and the pump is not using electricity. Whenever the water tank temperature is below 55 °C and the SOC of the TCM tank is over 10%, the water storage is recharged from the TCM by turning on the pump between the TCM system and the water tank, and also the pump between the TCM storage and the borehole, to deliver the corresponding evaporation heat. The pumps are turned off again when the water tank reaches 63 °C or the TCM storage SOC gets below 10%. Since the borehole temperature was now subject to change, resulting in a varying vapour pressure and a corresponding varying reaction equilibrium temperature, a slightly higher DH of 66 kJ/mol was used to make sure that the equilibrium temperature would not get below the 63 °C setpoint of the water tank. It was assumed that 3 moles of water could be attached per mole of salt and the resulting TCM storage capacity was 6.6 GJ. The simulation time was increased to two years.

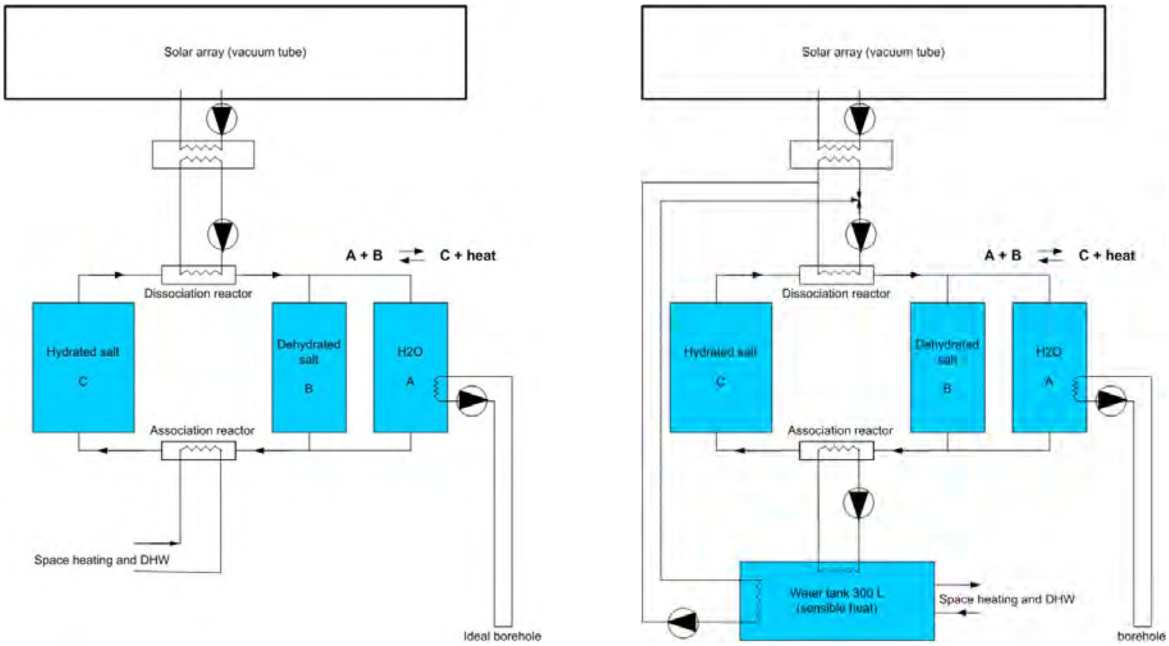

Figure 2: Schematical presentation of ECN TCM heat storage unit. LEFT**: first set of calculations,** RIGHT: **second set of calculations**

2.2 Definition of the components included in the system and standard inputs data

2.2.1 General Settings in the TRNEDIT template

Some parameters, such as collector area, building type and climate were varied during the calculations. In addition, some parameters such as described above were also changed between the two sets of calculations (e.g. first set 13 months calculations, second set 2 year calculations). Here, the parameters that were chosen as fixed during the second set of calculations are presented:

General Settings (to be chosen by TRNEDIT):

Main	
simulation timestep	1/20 h
tolerance integration / convergence	0.003 / 0.003
length of simulation	24 months
climate	Zürich / Stockholm / Madrid
building	SFH100 / SFH60 / SFH15
Auxiliary	
Nominal Power of Auxiliary	10 kW
Set temperature Auxiliary into store	63 °C
Auxiliary temperature rise	10 K
Collector	
type	Evacuated tube col. (ref)
aperture area	5 / 10 / 20 / 40 m^2
tilt angle	45°
azimuth (0° = south, 90° = west, 270° east)	0°
primary loop specific mass flow rate	15 $kg/h/m^2$
upper / lower dead band (switch on / off)	7 K / 4 K
relative height of low temperature sensor in store	0.1
cut-off temperature of collector	90 °C

boiling temperature of collector fluid	100 °C
Water Store	
storage volume	0.3 m^3
insulation thickness (λ=0.042 W/mK)	0.15 m
correction factor for heat loss	1.4
Borehole Settings:	
Storage volume	5715 m^3
Flow rate	1800 kg/hr
Borehole depth	160 m
Borehole radius	0.065 m
Outer radius of U-tube pipe	0.02
Center-to-center half distance	0.043
Conductivity	3.5 kJ/hr/m/K
Heat capacity	2200 kJ/m^3/K
Number of boreholes	1
Number of preheating years	0
Number of radial / vertical regions	10 / 10
Average ambient temperature (corresponding to climate)	9 °C / 6.9 °C / 13.5 °C
TCM storage Settings:	
Starting mass anhydrate	2000 kg
SOC at start	0.5
Reaction enthalpy per mole of water vapour DH	66 kJ/mol
Number of water vapour atoms per hydrated atom	3
Heat capacity TCM on/off	off
Flow rate TCM tank to water tank	100 kg/hr
Flow rate solar collector array to TCM tank	Same as collector flow rate to water tank

One of the inputs required by the borehole model is the average ambient temperature. This was calculated with the program Meteonorm for the three climates studied (for Stockholm 6.9 °C was found, for Zurich 9 °C and for Madrid 13.5 °C). This temperature was defined as a constant in the program.

The approximate volume for the TCM store, including all vessels and reactors, is 1.5 m^3/GJ of stored energy. Thus a store size of 6.6 GJ has an approximate volume of 10 m^3.

2.3 Validation of the system model

Experimental validation is not yet possible, since measurements have not yet been taken.

3 Simulations for testing the library and the accuracy

First, in order to be able to run the program at all, some version problems had to be solved; since additional types such as type 155 had to be added to the template, the template dll file was not sufficient to run the model and separate types had to be added. However, this also required the use of the corresponding version of the TRNSYS package. It turned out that the latest version of the TRNSYS package could not run the template, and that an older version had to be used. Similarly, the older TNSYS version also required an older version of Matlab. It took some time to get all this sorted out and get the program running with the correct versions.

In the validation for the first set of runs, it was found that the energy balance was not correct, due to the fact that the TRNSYS program had several iteration steps per time step. The Matlab TCM storage model did not take this into account, so at every time step the TCM model was charged or discharged several times (the number of iteration steps), resulting in a much too fast depletion or loading of the TCM storage. Once the effect was found, this was easily remedied by setting the type 155 parameter 4 to non-iterative. For the second set of simulations, Figure 3 shows the deviation in the energy balance over the TCM tank over the two years of the calculation. It is clear that this error is very small.

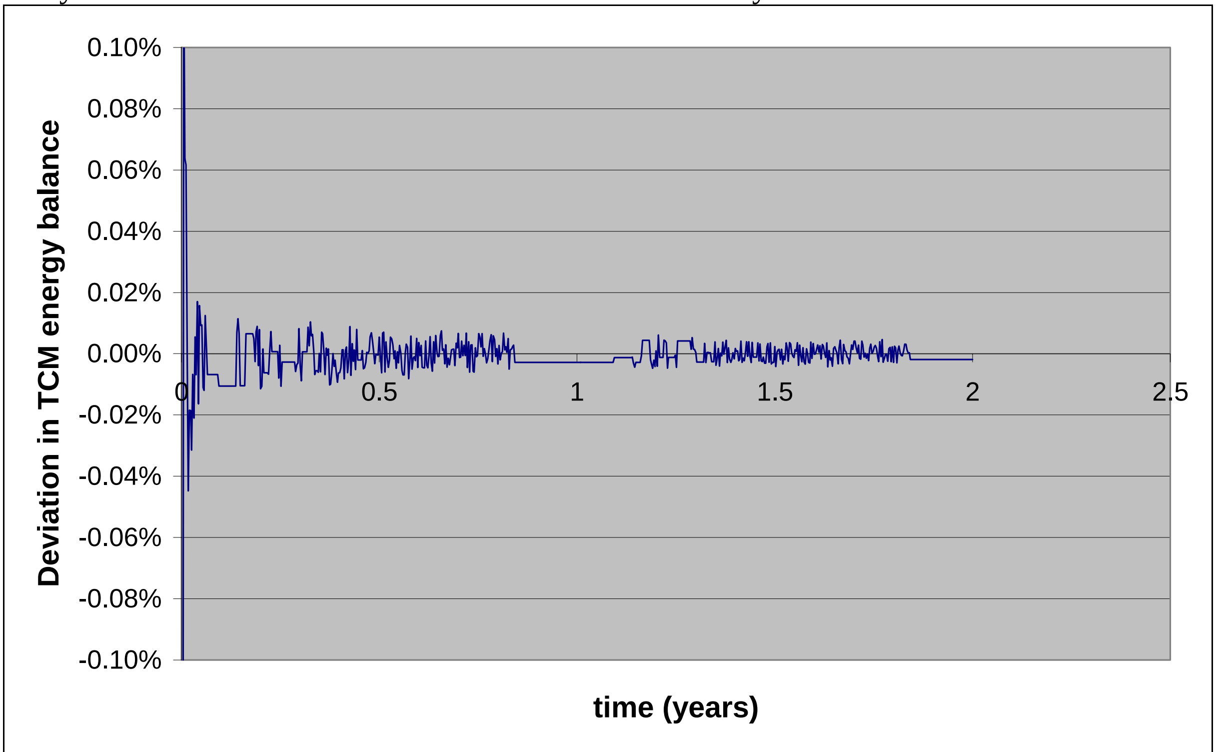

Figure 3: Error in energy balance TCM tank as a percentage of energy supplied from the TCM tank to the water tank.

In the second set of simulations, for the type 557 borehole model the parameters were used as supplied within the task, but with the addition of 18 preheating years. However, this preheating resulted in too high borehole temperatures (starting borehole temperatures between 15 °C to 25 °C, which was probably related to too high parameter settings for the maximum and minimum borehole preheat temperature). Since it was not clear what values for the minimum and maximum preheating temperatures should be used, and since they would in any case depend on the climate and the system dimensioning (while a large amount of different combinations of these two were to be calculated for the task), it was decided finally not to do any preconditioning at all and set the number of preheating years to zero. In Figure 4, the borehole temperature over the 2 years of the simulation is shown.

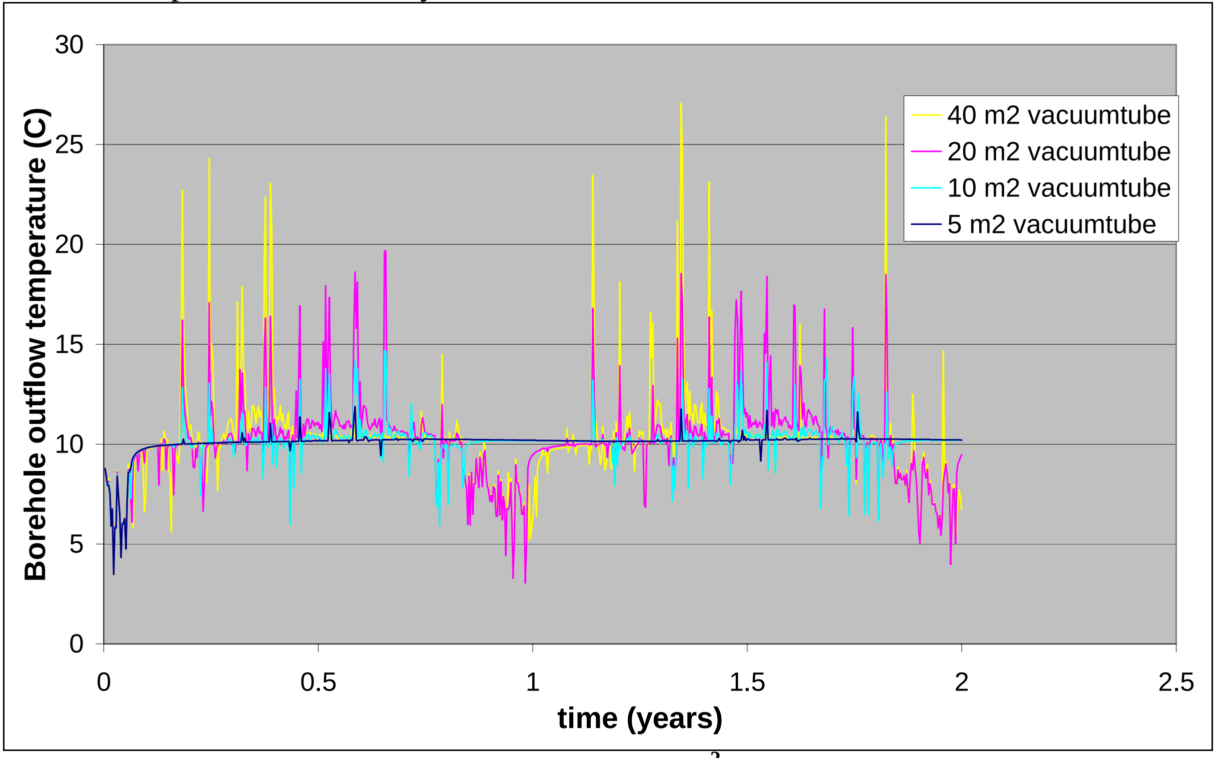

Figure 4: Borehole temperature (Zürich, 15 kWh/m^{2}a)

4 Sensitivity Analysis

4.1 Presentation of results

4.1.1 Introduction

Since the ECN research on thermochemical storage is presently mainly focusing on materials research, it was considered interesting to vary the materials characteristics to investigate their effects on the savings that can be obtained with a TCM storage. Therefore, characteristics such as DH (the enthalpy of reaction per mole of water) and the heat capacity of the TCM material were varied. For the variation in heat capacity, the difference was calculated between ignoring the TCM material heat capacity in the simulations altogether or giving it a realistic value (in the figures indicated as cps=0 (=off) or cps=1 (=on)). In all simulations, however, the heat capacity of the reactor itself was ignored, which will be significant in a real system. Also, the system design was varied, to be able to optimize the system. In the simulations, the effects of TCM storage capacity and collector type were varied, in addition to the standard variation in collector area (and therefore in FSC). For both the first and the second run of simulations, the results are shown in the following two paragraphs. The store volume is approximately 1.5 m^3/GJ of stored energy.
In the calculations in this section, just 4 points on the FSC curve have been calculated, corresponding to 4 different collector areas, while the climate was kept fixed at Zürich and the building type at 15 kWh/m^2/a.

4.1.2 First set of calculations

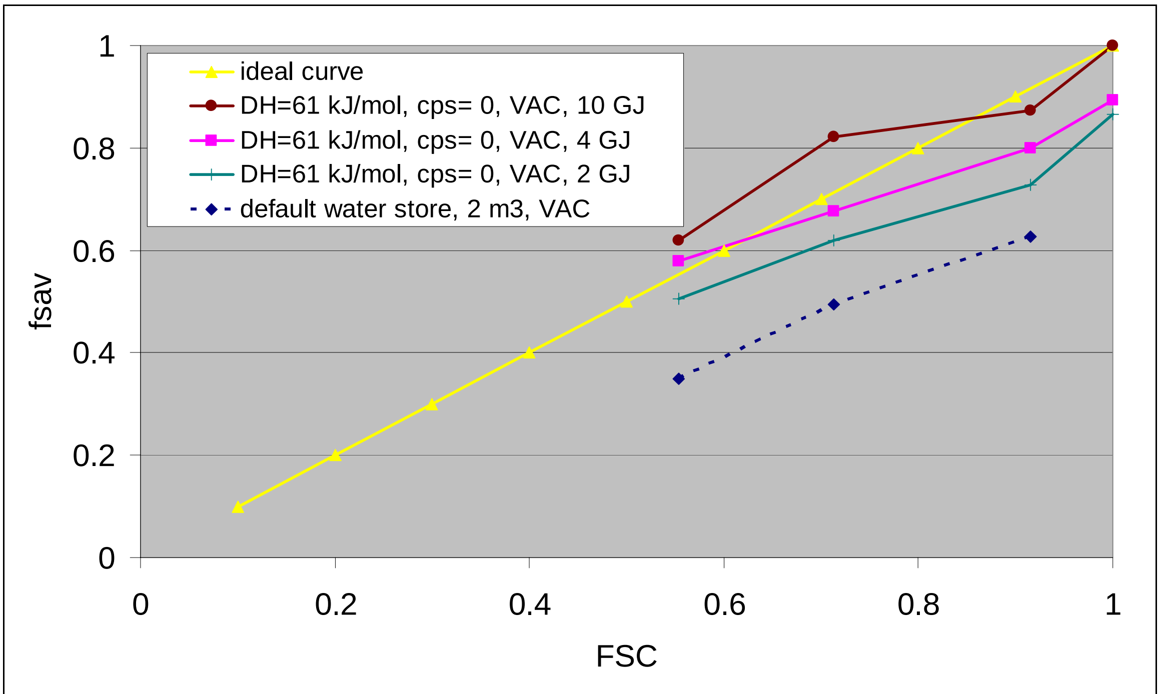

Figure 5: Effect of storage size (climate Zürich, building type 15 kWh/m^2)

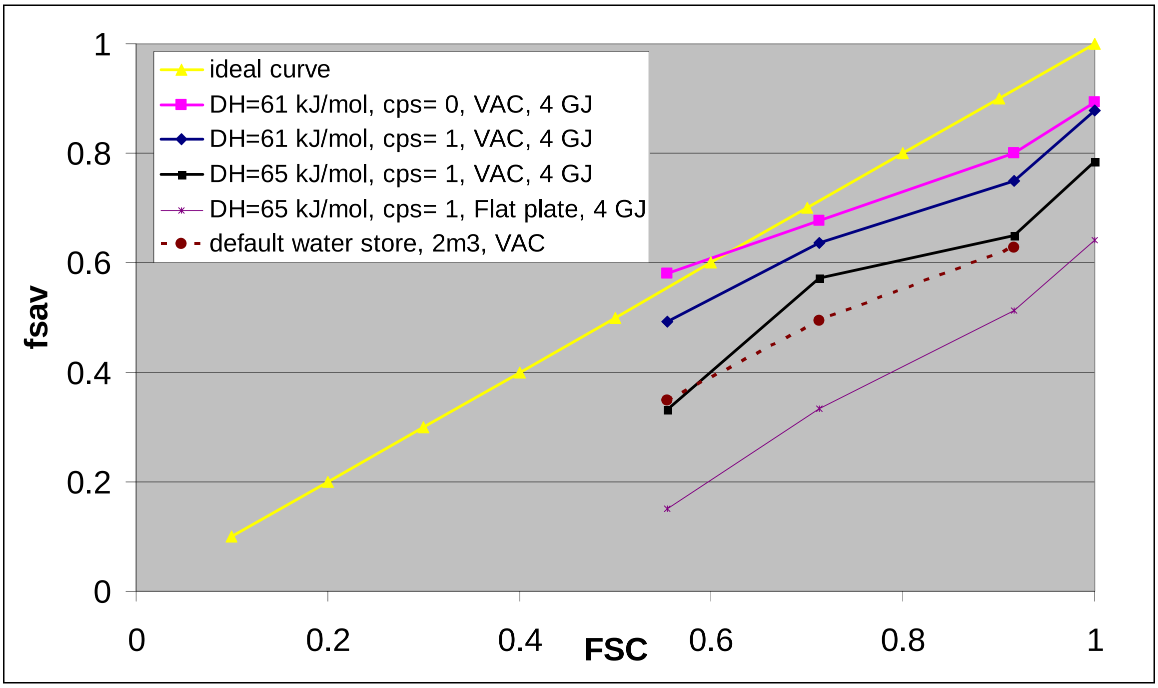

Figure 6: Effect of collector type, thermal capacity and DH (climate Zürich, building type 15 kWh/m^2)

In Figure 5, the TCM storage capacity is varied from 2 to 10 GJ. The results indicate that very large savings ca be obtained if the storage tank is large enough. However, even for a tank as small as 2 GJ, the simulations indicate that over 80% savings could be obtained in a system with a 40 m^2 vacuum tube area for the present building and climate.

Figure 6 shows the effect of varying the enthalpy DH and the thermal capacity of the TCM material. The effect of the heat capacity of the material is small but significant. Increasing DH leads to a significant reduction in the savings that can be obtained. This will be due to the increase in the temperature required for charging the TCM, which reduces the collector output power. This effect becomes even more pronounced if a flat-plate collector is used instead of a vacuum tube system, in which case the savings are strongly reduced.

4.1.3 Second set of calculations

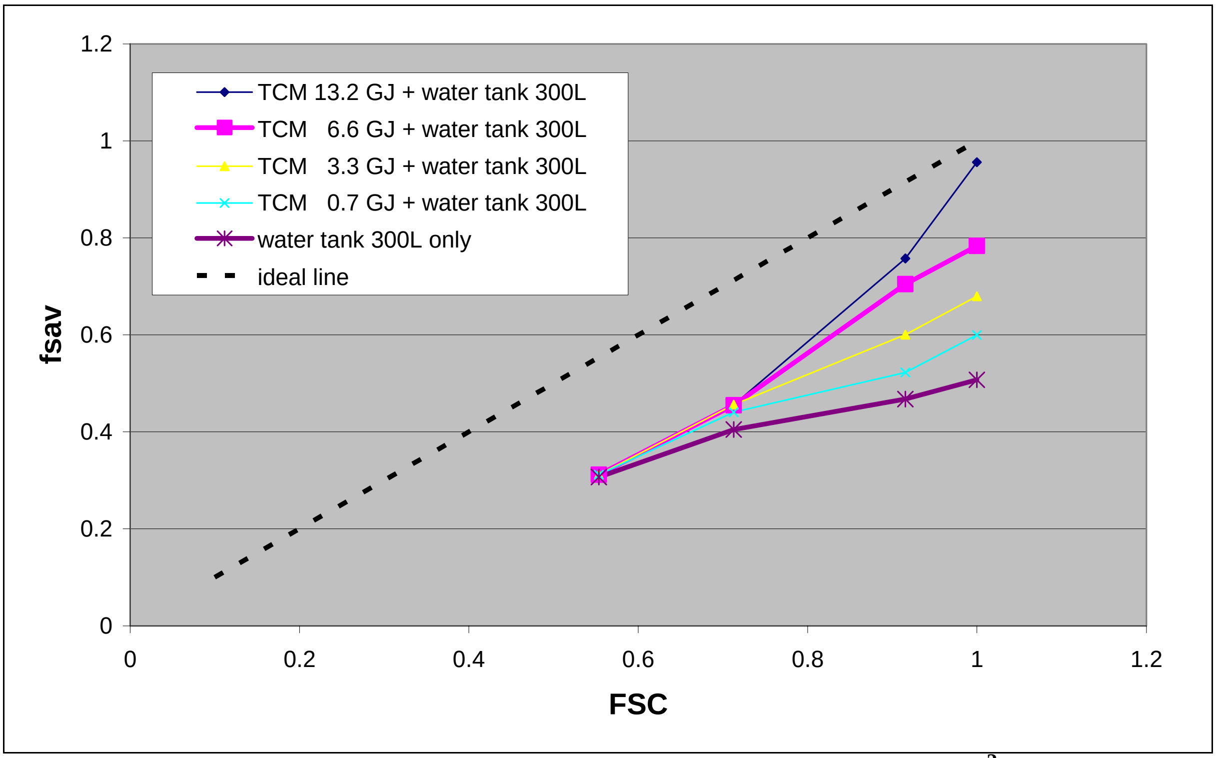

Figure 7: Effect of TCM storage capacity on savings (Zürich, 15 kWh/m^{2}a)

Figure 7 shows the effect of TCM storage capacity for the conditions of the second set of calculations. First of all, it can be seen that the savings are reduced, compared to the results for the first set of calculations. This will largely be due to the increase in DH (which was 66 kJ in the second set, versus 61 kJ in the first set; see also the large effect of increasing DH from 61 to 65 kJ in Figure 6) and also to the sensible losses of the additional water tank. In addition, the control determining the charging of the water storage or the TCM storage may need further optimisation.

A second conclusion is the fact that very large savings can be obtained if the TCM storage and the collector area are both large enough; for the 13.2 GJ TCM storage system and 40 m^2 of vacuum tube area, savings of over 95% were found. The store volume is approximately 1.5 m^3/GJ of stored energy.

A third conclusion is the fact that for low collector areas, the TCM storage has only very little effect since it cannot be charged effectively; for an FSC of 0.55 (corresponding to 5 m^2 vacuum tube area in this calculation) almost no effect of the additional TCM storage is found, whereas for high values of FSC, a substantial increase in fsav appears, relative to the water tank. Clearly, at low values of FSC, the collector area mainly charges the water storage and hardly ever gets to charging the TCM storage, as is also clearly seen in the SOC graph shown in Figure 8. This figure also indicates that, for a system with a 10 m^2 vacuum tube array, only about 0.9 GJ of the TCM storage capacity is used effectively, and increasing the storage capacity over this value is only useful if also the collector array is increased further.

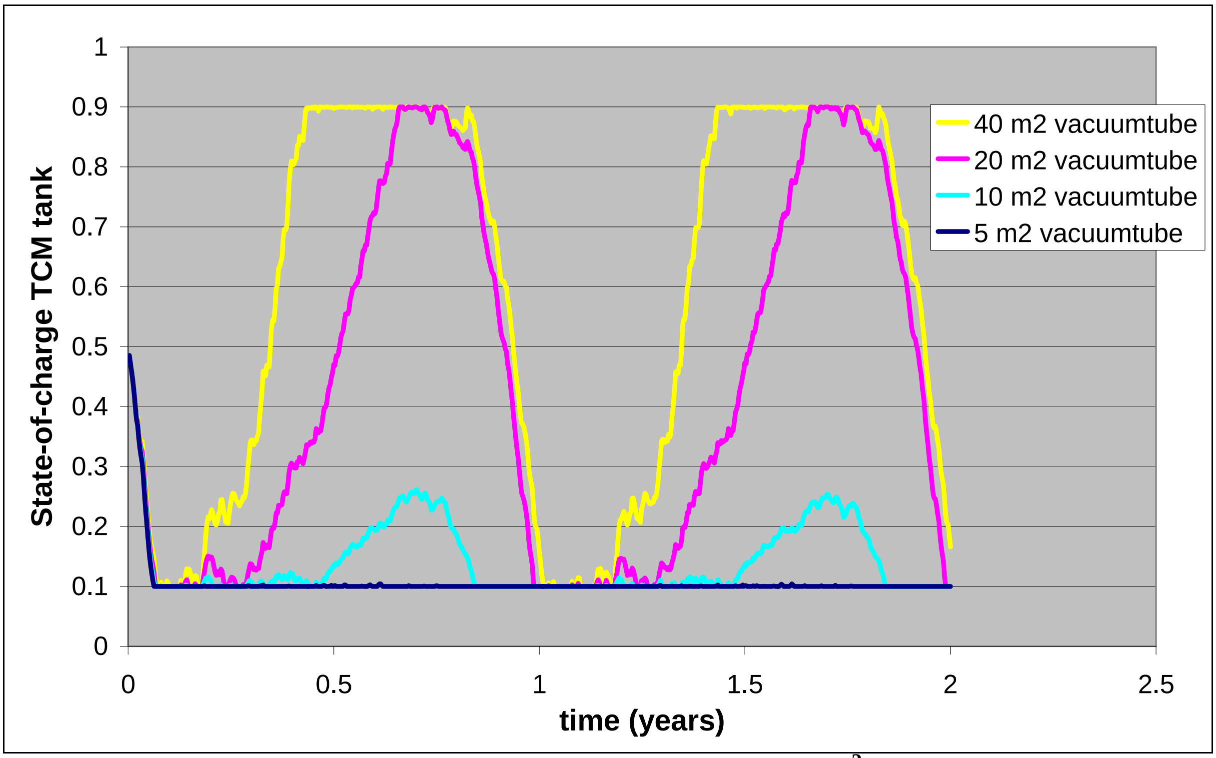

Figure 8: State of charge of the TCM tank (Zürich, 15 kWh/m^{2}a, TCM storage capacity 6.6 GJ)

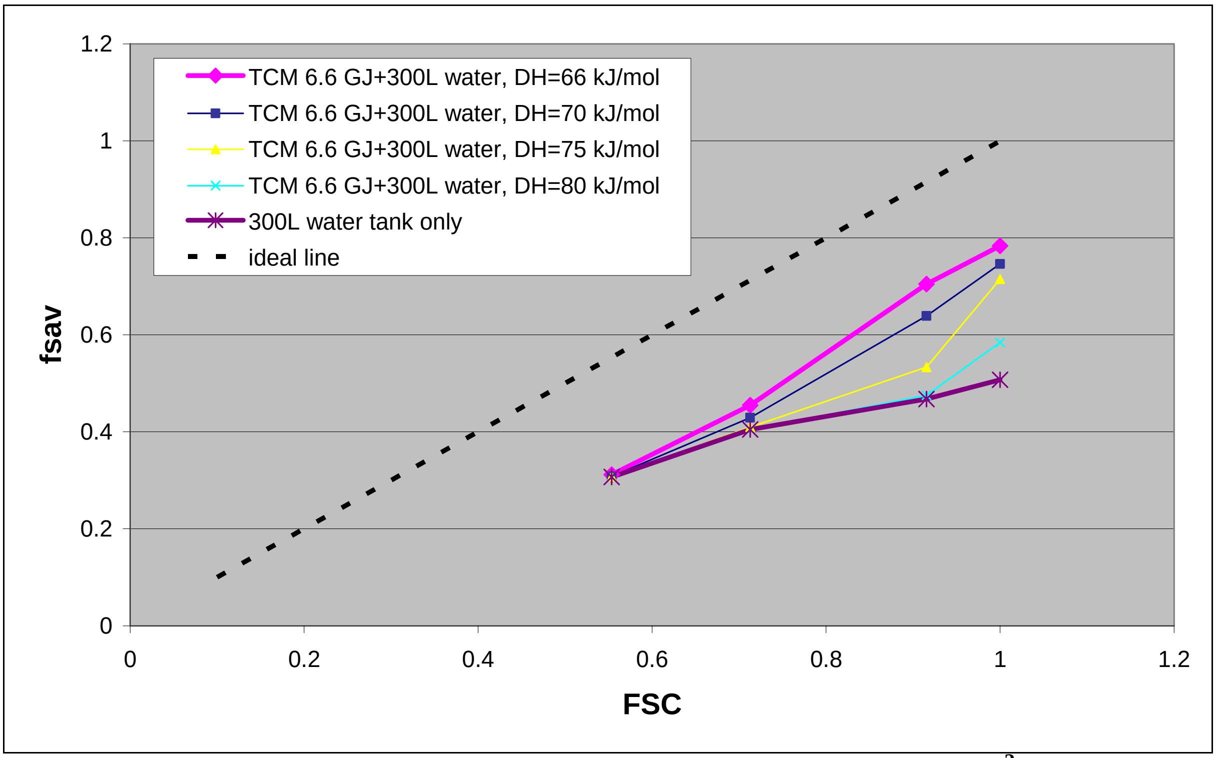

Figure 9: Effect of TCM reaction enthalpy on savings (Zürich, 15 kWh/m^{2}a)

Figure 9 shows that on changing the enthalpy for 66 kJ/mol (about 80 °C equilibrium temperature) to 80 kJ/mol (about 150 °C equilibrium temperature), while keeping the total storage capacity fixed at 6.6 GJ, it is clear that a large reduction occurs in saving potential. This is due to the fact that the charging temperature of the TCM tank becomes too high for effective charging with the solar array. The reduction in savings corresponds to similar findings in the first set of calculations. In addition, this result underscores the importance of using good vacuum tube collectors that can provide the high temperatures required by the TCM.

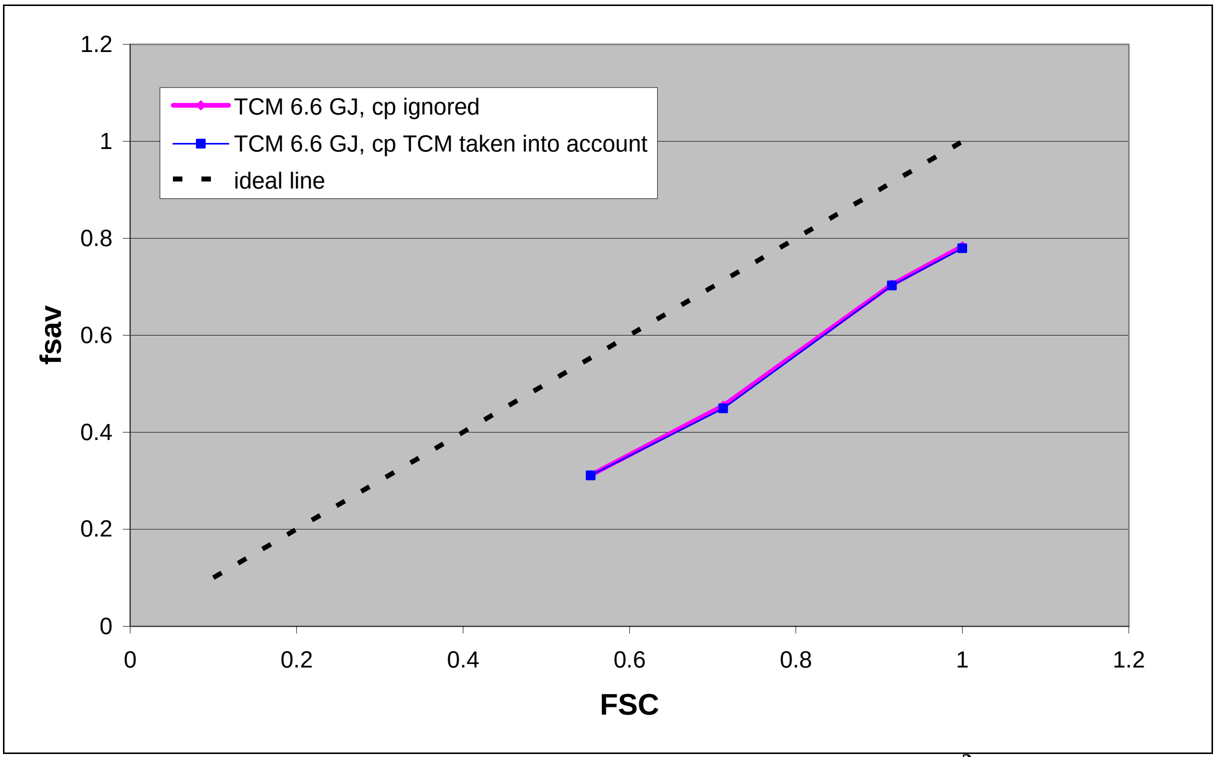

Figure 10: Effect of TCM heat capacity on savings (Zürich, 15 kWh/m^{2}a)

Finally, in Figure 10 it can be seen that in the present set of calculations, there is almost no effect of the thermal capacity of the TCM material; the difference is less than 0.4% absolute. This is different from the results of the first set of calculations, which indicated a small but significant effect. The difference is probably related to the fact that in the system used in the first set of calculations, the entire load was provided by the TCM storage (the auxiliary heater also providing heat to the TCM storage), whereas in the second set of calculations, only a part of the total load is provided by the TCM storage via the water tank (at most about 30% for FSC=1), and the remainder is provided directly by the solar array and the auxiliary heater via the water tank, without involvement of the TCM storage. Nevertheless, it should be realised that the sensible losses due to the thermal capacity are underestimated by the present calculation, since the thermal capacity of the reactor itself is ignored, which can be expected to have a large effect in a real system.

5 Analysis using FSC

5.1 First set of calculations

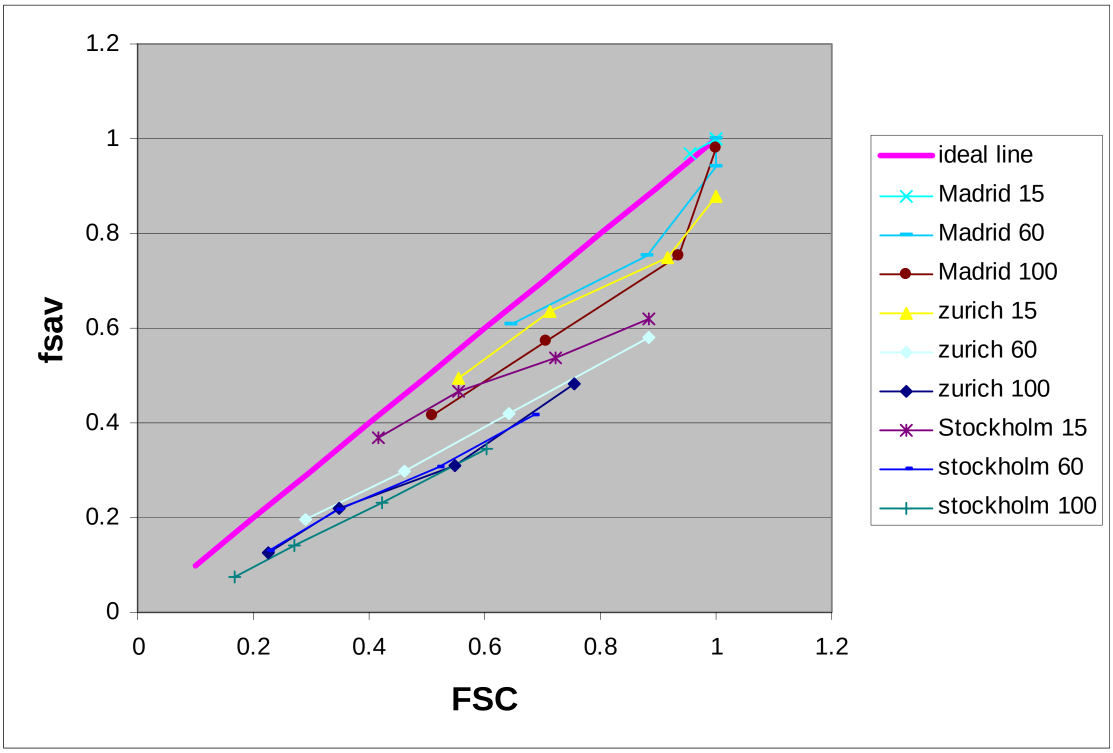

Figure 11: FSC for 4 GJ TCM storage, various climates (Madrid, Zürich, Stockholm) and house types (100 kWh/m^{2}a, 60 kWh/m^{2}a, 15 kWh/m^{2}a). FSC was varied by changing the collector area over the range 5-10-20-40 m^2.

5.2 Second set of calculations

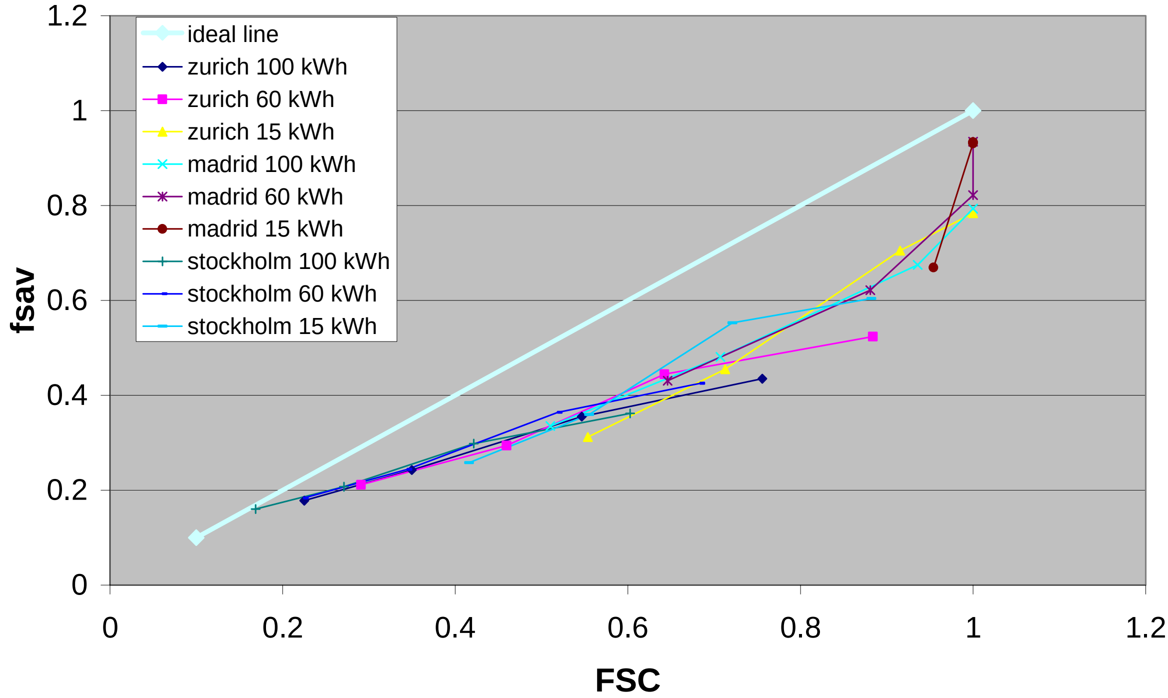

Figure 12: FSC for 6.6 GJ TCM storage, various climates (Madrid, Zürich, Stockholm) and house types (100 kWh/m^{2}a, 60 kWh/m^{2}a, 15 kWh/m^{2}a). FSC was varied by changing the collector area over the range 5-10-20-40 m^2.

Clearly, in the second set of calculations, losses are higher. This will largely be due to the higher DH (increased from 61 kJ/mol in the first set of calculations to 66 kJ/mol in the second set) and also to the sensible losses of the additional water storage tank. Also, the non-ideal borehole will have some effect, although in general it was found that the temperatures did not deviate too much from the average ground temperature (see Figure 4).
In addition, it can clearly be seen that in the second set of calculations, the lines of Figure 12, the calculated systems are converging much more towards one curve than for the first set of calculations. This may well be related to the fact that for the first set, only 13 months were calculated, which will have resulted in TCM storages that were not yet in annual thermal equilibrium (net charging or discharging over the year). The effect of this would be that in the first set of calculations for small values of FSC, the TCM system would display a net discharging, resulting in a too high contribution to the savings, while for high values of FSC, the system would display a net charging, providing a too low contribution to the savings, the combined result being a curve tilted towards the horizontal, which is exactly what becomes apparent in comparing Figure 11 to Figure 12.

If all the simulation results are plotted according to the FSC’ variable, allowing values of FSC>1, it can be seen (Figure 13) that the results for smaller FSC’ values (very nearly identical to FSC values, see report A3) the curves lie together. However, for larger FSC’ values, and more specifically for larger collector areas, the individual curves tend to “saturate” by levelling off towards a limited fractional savings value. This is presumably due to the saturation of the store as the size of the store is constant and there is thus much smaller storage capacity per m^2 collector area, as shown in Figure 8. In the appendix, also the results presented in Figure 7, Figure 9 and Figure 10 are plotted versus FSC’.

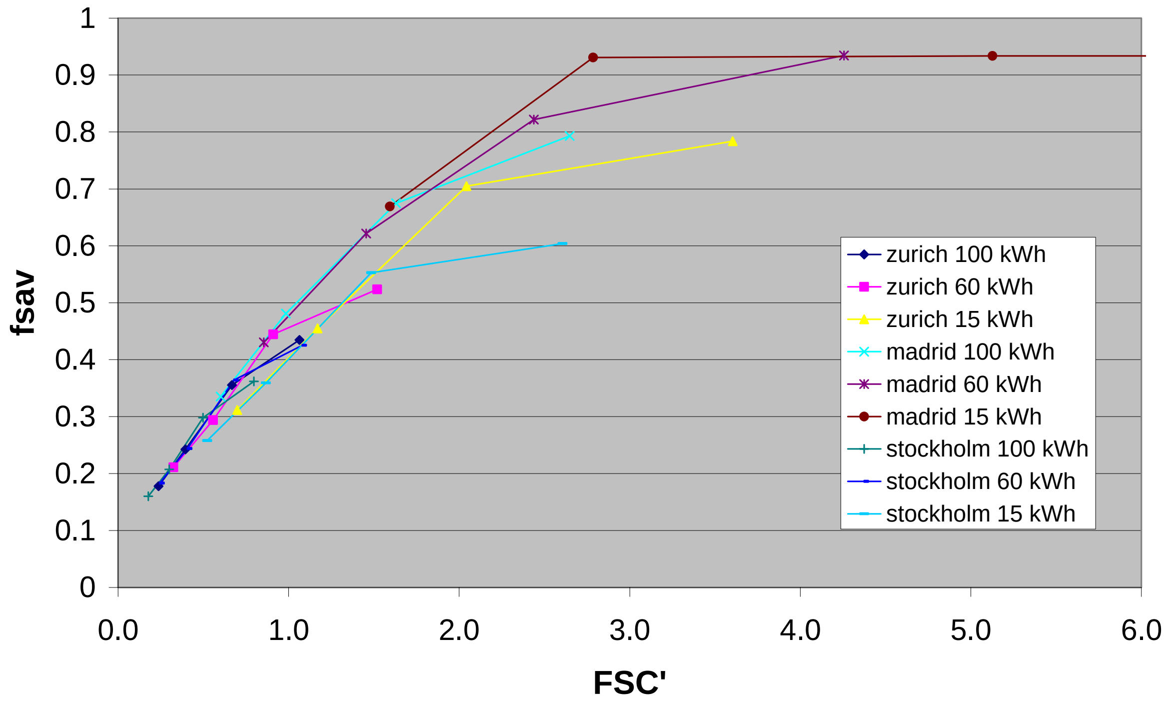

Figure 13: FSC' for 6.6 GJ tank, various climates (Madrid, Zürich, Stockholm) and house types (100 kWh/m^{2}a, 60 kWh/m^{2}a, 15 kWh/m^{2}a). Same simulation results as Figure 12.

6 Lessons learned

The TCM storage can add substantially to the solar fraction of the house. The system works best in combination with a sufficiently large vacuum collector array. A TCM material with an optimal DH (leading to an equilibrium temperature high enough for the load yet low enough for the solar system) must still be selected and tested. Furthermore, it is important to optimise the control of the entire system, distributing the solar energy between the water tank and the TCM storage in an efficient way. Finally, thermal capacity effects will be small for a TCM storage with separate reactor.

7 References

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8 Acknowledgement

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9 Appendix

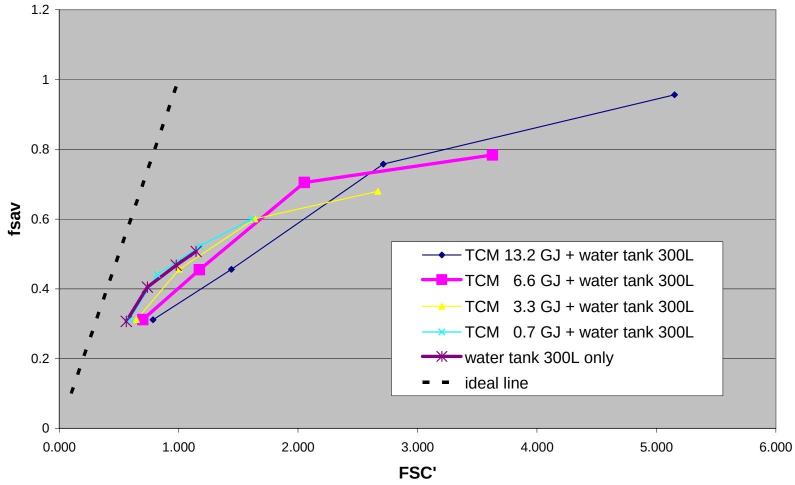

Figure 14: Effect of TCM storage capacity on savings (Zürich, 15 kWh/m^{2}a, DH=66kJ/mol). Same simulation results as Figure 7.

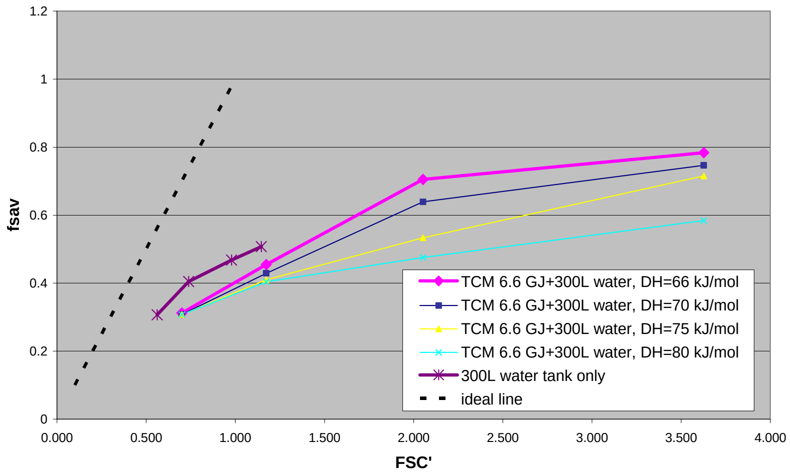

Figure 15: Effect of TCM reaction enthalpy on savings (Zürich, 15 kWh/m^{2}a, TCM storage capacity 6.6 GJ). Same simulation results as Figure 9.

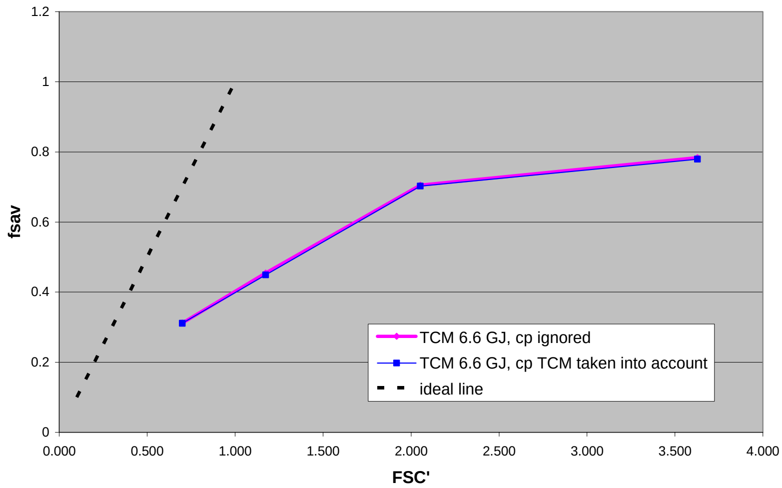

Figure 16: Effect of TCM heat capacity on savings (Zürich, 15 kWh/m^{2}a, TCM storage capacity 6.6 GJ). Same simulation results as Figure 10.