Final report

1.1 Project details

Project title	IEA Task material and component development for thermal storage systems
Project identification (program abbrev. and file)	IEA Task 58
Name of the programme which has funded the project	EUDP
Project managing company/institution (name and address)	DTU Civil Engineering, Technical University of Denmark, Building 118, Brovej, 2800 Kgs. Lyngby
Project partners	-
CVR (central business register)	30 06 09 46
Date for submission	December 31, 2019

1.2 Short description of project objective and results

The aims of the project are, within the IEA (International Energy Agency) SHC (Solar Heating & Cooling) Programme Task 58 project "Material and component development for thermal storage systems", to develop compact long term heat storage based on salt hydrates and to elucidate the suitability of PCM (Phase Change Material) heat storages for different applications.

The project showed that PCM heat storages with stable supercooling can work in a reliable way as compact combined short and long term heat storages, and that combined short and long term PCM heat storages are suitable for future solar heating systems where the heat storage can be charged both with solar heat and cheap electricity in windy winter periods.

Projektformålet er dansk deltagelse i IEA (International Energy Agency) SHC (Solar Heating & Cooling) Programme Task 58 projektet "Material and component development for thermal storage systems". I projektet udvikles et kompakt langtidsvarmelager baseret på et stabilt underafkølende salthydrat og egnetheden af kompakte smeltevarmelagre til forskellige formål vurderes.

Projektet viste at smeltevarmelagre med stabil underafkøling kan fungere pålideligt som kompakte kombinerede korttids- og langtidsvarmelagre og at kombinerede korttids- og langtidsvarmelagre er velegnede til fremtidens solvarmeanlæg, hvor varmelageret både kan oplades med solvarme og med billig el i vindrige vinterperioder.

1.3 Executive summary

The main objective of the research was within the IEA (International Energy Agency) SHC (Solar heating & Cooling) programme Task 58 project "Material and component development for thermal storage systems" to develop attractive long term heat storages for different applications. Focus was on three fields: Component development, applications and numerical methods. By means of the investigations the suitability of compact long term heat storages was elucidated for different applications.

The heat storage material used in most of the investigated heat storages is SAT, sodium acetate trihydrate, with different additives. This material was used due to its high heat of fusion, a suitable melting point of 58°C and its ability to supercool in a stable way. By means of the stable supercooling, heat storage periods without heat loss can be achieved.

Heat storage modules from Nilan A/S and H.M. Heizkörper have been investigated experimentally. The investigations were focused on the heat content of the modules, the heat exchange capacity rates to and from the modules, the stability of the supercooling, the long term stability of the modules and on different methods to initiate solidification. The investigations demonstrated that PCM heat storages with stable supercooling can work in a reliable way.

The suitability of different applications for PCM heat storages were investigated by means of theoretical investigations based on numerical methods. Simulation models for solar heating systems with combined long term and short term PCM heat storages and for heat pump systems with PCM heat storage were developed. Calculations with the models were carried out in order to determine suitable heat storage solutions for the different systems.

The project results are valuable in connection with the future development and use of compact combined short and long term heat storages for renewable energy systems.

1.4 Project objectives

The aims of the project were to participate in the IEA (International Energy Agency) SHC (Solar Heating & Cooling) Programme Task 58 project "Material and component development for thermal storage systems", to develop compact long term heat storage based on salt hydrates and to elucidate the suitability of PCM (Phase Change Material) heat storages for different applications.

The participation in the IEA Task 58 project focused on contributions to three fields: Component development, applications and numerical methods. DTU Civil Engineering participated in all the expert meetings of the project and contributed to the work packages, presentations and publications of the project.

Further, the project showed that PCM heat storages with stable supercooling can work in a reliable way as compact combined short and long term heat storages, and that combined short and long term PCM heat storages are suitable for future solar heating systems where the heat storage can be charged both with solar heat and cheap electricity in windy winter periods.

The project was carried out as planned. The following gives a description of how the milestones of the project were reached.

Milestone M1.1: Nilan heat storage module installed in the heat storage test facility was reached as originally planned. In the heat storage test facility the cylindrical tank-in-tank heat storage with an internal spiral heat exchanger was investigated experimentally to clarify the following aspects:

- Can stable supercooling of SAT be utilized with this inexpensive heat store?
- Energy storage capacities for full charge, short and long-term heat storage based on a series of test cycles
- How does the SAT composite perform in comparison to water?
- Comparison of spiral- and mantle heat exchanger performance with different flow rates
- Is the heat transfer from the SAT composite to water sufficient to enable domestic hot water (DHW) and space heating (SH) supply in terms of flow temperature and power?

Sufficient measurement accuracy was ensured by calibration of sensors of the heat storage test facility.

Milestone M1.2: Suitability of Nilan heat storage module elucidated was reached as originally planned. The results presented in section 1.5 are valuable knowledge in pursue of developing economically attractive compact thermal energy storages that are more efficient than water storages. The investigation shows the potential differences between water and PCM heat storages and elucidates the way of operating a low cost PCM heat storage for optimal performance.

Spontaneous solidification during supercooling of SAT composite is the main risk for failure in the long term heat storage process. In five storage cycles crystallization started from the top of the inner tank volume. Later inspection showed a corroded top surface of the inner tank with traces of salt, which was not in contact with the SAT composite. It is assumed that nucleation seeds could remain there and eventually fall on the supercooled SAT composite during cool-down. Other explanations could be that open thermocouple wires were not suitable for testing and that one of the top-flanges of the inner tank lost tightness. Despite the open thermocouple wires and corroded inner tank surfaces low supercooling temperatures were achieved. With 12 full test cycles performed, the measurements were sufficient for energy storage capacity and heat transfer analysis.

For an improved heat store (ongoing industry collaboration in projects), the above mentioned problems could potentially be avoided by:

- Using oil instead of air in the expansion volume in the inner tank to avoid corrosion
- Design of the inner tank with a single, well-sealed opening for filling and pressure compensation
- No internal temperature monitoring

Milestone M1.3: Heat storage design for heat pump systems elucidated was reached as originally planned. The salt hydrate sodium thiosulfate pentahydrate, $Na_2S_2O_3 \cdot 5H_2O$, with a melting point of 48°C was used as heat storage material. The relative low melting point is resulting in a relatively high efficiency of the heat pump. The heat storage material is macro encapsulated in a number of small polymer units with relatively high ratios between heat transfer area and PCM storage volume. A high number of the polymer units with the PCM are placed in a vertical cylindrical tank. Water, which is surrounding the units in the tank, is used to transfer heat to and from the heat storage. The design of the heat storage secures a good heat transfer to and from the heat storage and at the same time the heat storage is relatively inexpensive.

Milestone M1.4: Optimal heat storage tested was reached as originally planned. The results of the experimental investigations of the Heizkörper heat storage described in section 1.5 showed that that PCM heat storages with stable supercooling can work in a reliable way with sufficiently high heat exchange capacity rates for normal energy systems and houses.

All M1 milestones inclusive development of PCM heat stores are reached as originally planned.

Milestone M2.1: Simulation model for solar heating system developed was reached as originally planned.

Before the start of the project the application potential of the developed short and long term PCM heat stores utilizing stable supercooling of SAT has never been investigated. The following points were addressed in the project:

- A validated simulation model for solar heating system with short and long term PCM heat storage and hot water buffer tank was developed.
- Calculations with the simulation model on yearly system performance for a passive house under typical Danish weather conditions were carried out.
- Sizing of system components. Sensitivity analysis were carried out on optimal solar collector area and heat storages volumes.
- Integration into a future energy system: By power-to-heat conversion, buildings will serve as one possible source of demand flexibility in future electrical grids. The demand flexibility of solar heating systems with heat storages utilizing stable supercooling of SAT composites was investigated.

Milestone M2.2: Simulation model for heat pump system with PCM heat storage developed was reached as originally planned. A detailed TRNSYS simulation model of heat pump system with PCM heat storage was created based on a new PCM heat storage component with short and long-term supercooling ability and a new control component using smart control strategy.

Milestone M2.3: Optimal system designs determined was reached as originally planned. Numerical simulation results for full potential analysis of a solar combi system with a PCM heat storage utilizing stable supercooling of SAT are presented in section 1.5. The performance potential of the system was studied for a Danish passive house with different sizes and designs of the solar heating system. It was investigated how component sizing influences the solar fraction of the system. The potential for integration in a future energy system was elucidated in a scenario assuming full storage charge by wind power at the beginning of the year, when no solar heat production was available.

Further, numerical simulation results elucidated how best to design and size a heat pump system with a PCM heat storage. This was determined by means of parametric studies with the TRNSYS model by varying heat storage parameters and applying smart control strategies. The results of the calculations are presented in section 1.5. The performance of the system was studied for a typical Danish house with Domestic Hot Water (DHW) consumption and Space Heating (SH) demand under Danish Typical Meteorology Year (TMY) weather conditions. Among other things, the influence of using floating electricity prices in the control strategy was studied.

All M2 milestones inclusive optimal energy system/suitability of energy system are reached as originally planned.

1.5 Project results and dissemination of results

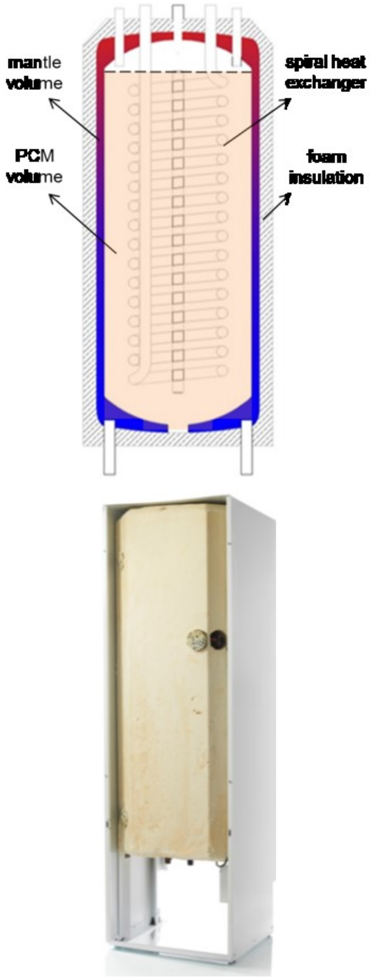
The following were considered by the development of PCM heat storages based on inexpensive heat storage units:

a) Due to their thermo-physical properties, SAT composites in liquid state enabled good heat transfer in vessels by allowing convection. During solidification, thermal conductivity decreases and no convective heat transfer is possible.
b) Rathgeber et al. [1] found that acceptable energy storage capacity costs of heat stores in buildings ranged from about 1 €/kWh for seasonal heat storage to 429 €/kWh for daily utilization. For industrial use SAT is available in large quantities, with market prices typically below 0.5 €/kg. For heat storage units containing 200 kg SAT composites in solar combi systems, monthly utilization of a heat storage capacity in the range of 15 – 27.4 kWh could be assumed. Thus, acceptable costs would be 100 - 460 €/heat storage unit. Therefore, an inexpensive heat exchanger and PCM container design is warranted.

Two heat storages were experimentally investigated. One heat storage produced by Nilan A/S and one heat storage produced by H.M. Heizkörper, Germany.

Experimental investigations on Nilan heat storage.

The tested cylindrical tank-in-tank heat storage prototype based on standard components of water heat stores appear from figure 1 and table 1. An inner steel tank contains SAT composite and an internal steel spiral heat exchanger as well as the mantle are used to transfer heat to and from the heat storage. That is: The inner tank is centred in an outer steel tank to realize heat exchange via its outer surface, the mantle heat exchanger. An installer friendly modular design was realized by rectangular shaped foam insulation and a metal cabinet with sufficient space for piping. An expansion vessel was placed on top of the cabinet.



Specifications of the heat	
PCM filling	200 kg
Inner tank	0.45 m
Inner tank height	1.20 m
Outer tank	0.50 m
Outer tank height	1.25 m
Heat transfer area	3.40 m^2
PCM volume	158 L
Water volume	59 L
Steel tank mass	140.8

Fig. 1: Photography of the cylindrical heat storage and schematic drawing of the intersection.

Table 1: Specification of the heat store.

Figure 2 presents the built test setup. It was used to investigate if the concept of stable supercooling can be utilized with the prototype heat store. Furthermore, if the heat transfer with spiral- and mantle heat exchangers is sufficient for DHW and SH supply in buildings. Energy storage capacities for full charge, short and long term heat storage were determined with a series of test cycles. The heat transfer properties of the store filled with water or the SAT composite were studied.

The heat storage was tested in a laboratory heat storage test facility with a 9 kW electric heater for charge and a plate heat exchanger for discharge. Water was used as heat transfer fluid. Performance evaluation was based on measurements of heat transfer fluid volume flow rates as well as inlet and outlet temperatures for the heat storage.

Fig 2: Test setup with graphical LabVIEW interface for live data reading.

A composite containing food-grade SAT (European standard 262i, IG Chemicals GmbH, Germany), 3 %wt. liquid polymer solution HD 310 (Suzhou Hongde Co. Ltd., China) and 2%wt. of extra water was chosen as PCM. Solidification of supercooled SAT composite was initiated by seed crystals which were inserted by an opening to the inner tank. The temperature of the SAT composite was measured with 12 thermocouples, distributed in the inner tank.

The heat exchange capacity rate (HXCR) was used to evaluate the ability to transfer thermal energy between the heat transfer fluid and the SAT composite:

$$HXCR\left(\frac{W}{K}\right) = \dot{V} * c_p * \rho * ln\left(\frac{T_{in}-\bar{T}_{PCM}}{T_{out}-\bar{T}_{PCM}}\right)$$

where the average SAT composite temperature ($\bar{T}_{PCM}$) was determined with a volume-based weight-model for the inner tank measurements. Tin is the inlet temperature of the heat transfer fluid and Tout is the outlet temperature of the heat transfer fluid. $\dot{V}$ is the volume flow rate of the heat transfer fluid flowing through the heat storage, c_p is the specific heat of the heat transfer fluid and ρ is the density of the heat transfer fluid.

12 test cycles were carried out in total. During all 12 test cycles, low supercooling temperatures were achieved, although temperature measurement devices and corrosion on the inner tank surface influenced supercooling stability.

The development of thermal power ($\dot{Q}$) and heat content of the store (Q_{store}) during a representative test cycle is presented in Figure 3. After charging (orange area) the SAT composite supercooled to ambient temperature and rested for a period of 12 hours (grey area). During SAT composite solidification (blue area) $\dot{Q}$ peaked at approximately 5 kW. The energy storage capacity of the store was measured to be 27 kWh for heat-up from 25 to 90 °C, whereas 15.5 kWh of heat was discharged in liquid state and 11.5 kWh of heat was stored in the supercooled PCM. The capacity of the composite was determined to be 21.3 kWh, which was 76 % higher than with water filled in the tank.

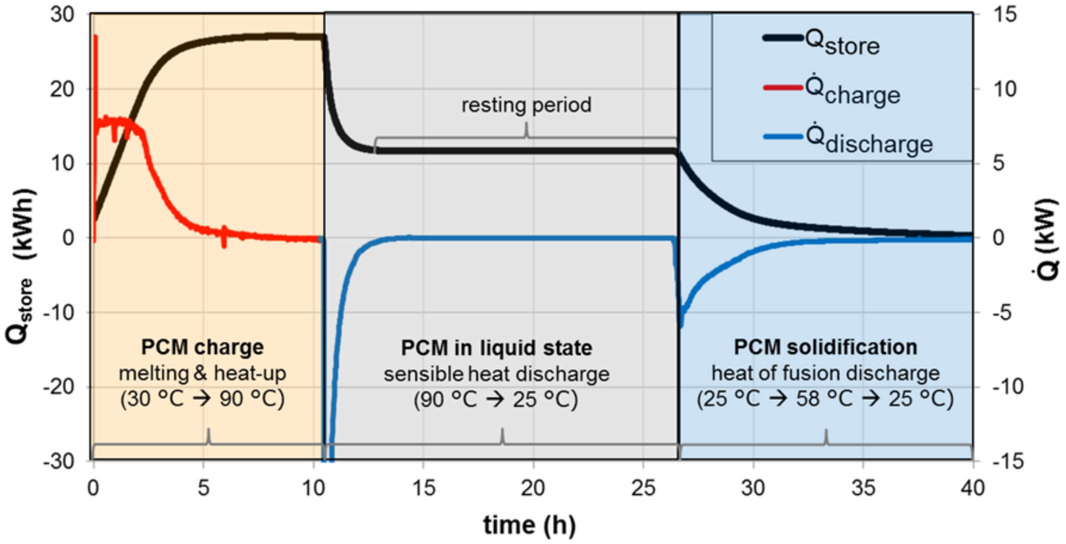


Fig. 3: Development of heat transfer rates and heat content during a selected test cycle.

HXCRs during charging and discharging of SAT composite did not change in the flow rate range of 3-10 L/min. This shows that the heat transfer was limited by the SAT composite. For charging, an average HXCR of 298 W/K was found, which was a factor of four lower than for water with a flow rate of 10 L/min.

Combined use of a spiral- and mantle heat exchanger with a flow rate of 2 L/min was advantageous during discharging of liquid SAT composite. Thermal stratification was utilized in the mantle, resulting in outlet temperatures (T_{out}) higher than $\overline{T}_{PCM}$. During solidification thermal power and outlet temperatures were rather low, and the effectiveness of heat transfer was reduced by a factor of three in comparison to liquid state.

Figure 4 presents data from a test cycle with discontinuous discharge. In liquid SAT composite state (grey area) T_{out} was higher than $\overline{T}_{PCM}$ until a heat content of 15 kWh was remaining. Then discharge was interrupted for the first time. Subsequently, discharge was conducted in seven parts, with intervals of 2-24 hours. Thus, it was possible to utilize heat of fusion with thermal power up to 4 kW (flow rate of 2 L/min) and with outlet temperatures close to that of the SAT composite. T_{out} exceeded 30 °C during all discharge parts, which is considered as requirement for SH and DHW supply in domestic dwellings.

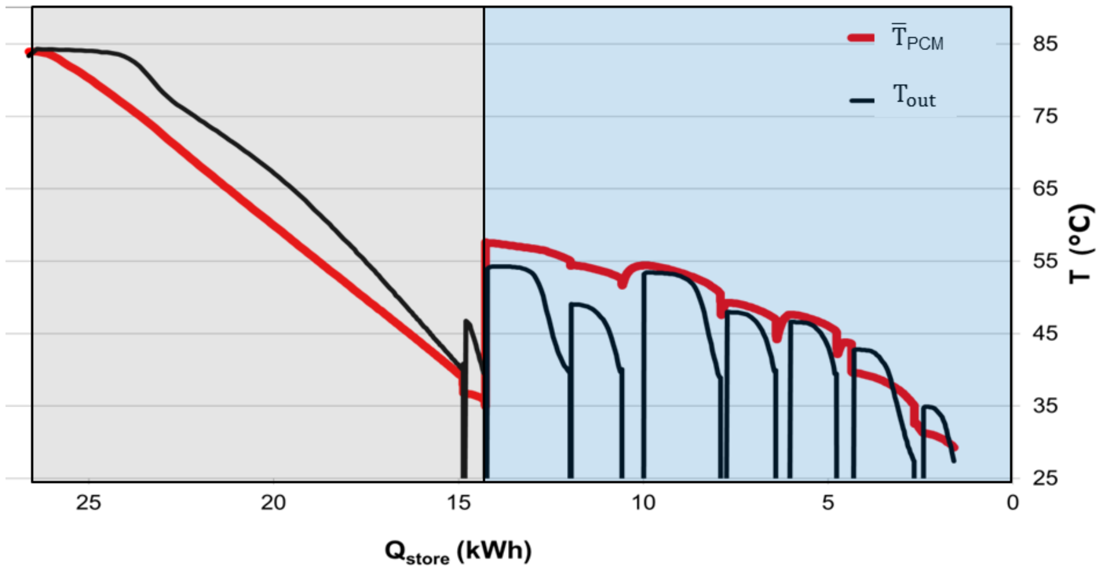


Fig. 4: Development of $\overline{T}_{PCM}$ and T_{out} during discontinuous discharge.

Experimental investigations on H.M. Heizkörper heat storage.

The tested cylindrical heat storage appear from figure 5. The height of the storage was 1.7 m, and the diameter was 0.4 m. 112 tubes were mounted vertically inside the storage, each with a length of 1.52 m and an inner diameter of 0.0276 m. The tubes were filled with 137.8 kg sodium acetate trihydrate with additives developed by H.M. Heizkörper. The additives were liquid polymers and extra water securing the long term stability of the heat storage. The tops of the tubes were fixed to a steel plate/manifold and open to the volume above the manifold plate where a layer of PCM made sure that all PCM in the tubes were joined in one volume. In this way it is possible to avoid pressure changes in the PCM part of the heat storage. The tubes in the cylinder were surrounded by water. The water is used as the heat transfer fluid during charge and discharge of the heat storage. The water volume surrounding the tubes in the heat storage was approximately 75 L.

The heat transfer fluid inlet was located at the bottom of the storage, and the outlet was located in the top of the storage water volume just under the steel plate. The inlet and outlet were placed on different sides of the tank. The storage was covered by an insulation layer to reduce heat loss. Figure 6 shows the top structure of the SAT heat storage. The top of the cylinder was made of glass. The SAT could be observed through the glass top. Figure 7 shows two pipes at the top of the heat storage. The inclined tube with an air filter prevents pressure changes in the PCM chamber. For triggering solidification of the supercooled SAT, the vertical pipe with a ball valve was placed on the top of the storage to drop crystals for start of solidification.

Fig. 5. The PCM heat storage unit with and without insulation.

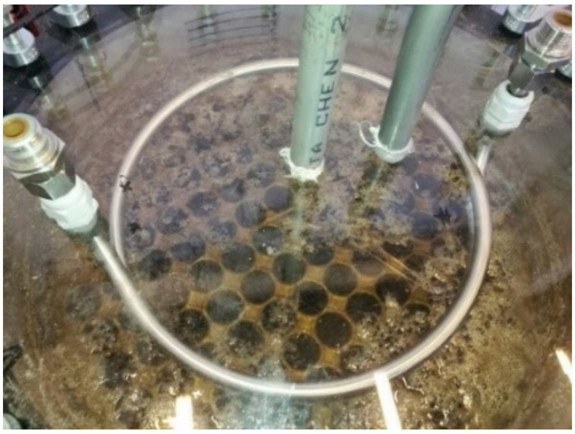


Fig. 6. The manifold plate with a view to the tube inside the storage through the melted PCM.

Fig. 7. Two pipes in the top of the PCM storage.

The heat storage including the shell and the tubes are all made of stainless steel. Figure 8 shows the heat storage in the heat storage test facility. There were 14 thermocouples placed in the storage. T1-T13 were placed on the outer surface of the cylindrical tank and covered by an insulation layer. T14 was inserted into the SAT inside one of the inner tubes.

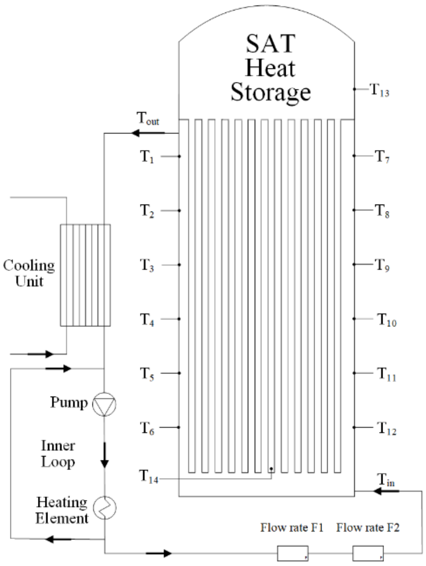


Fig. 8. Principle sketch of the tested heat storage in the heat storage test facility.

Fig. 9. The heat content change of the SAT heat storage in a theoretical cycle.

Figure 9 shows the heat content changes of the SAT heat storage in a theoretical cycle. The test cycle of the heat storage can be divided into 5 periods: Charge period (*a*-*b*-*c*-*d*), high-temperature steady state period (*d*-*d*), discharge period (*d*-*c*-*e*), supercooled standby period (*e*-*e*), and solidification period (*e*-*f*-*b*-*a*).

The heat storage was tested by means of charge and discharge tests. In the charge tests, the initial temperature (T_i) of the heat storage was 30℃. In the discharge tests, the initial temperature of the heat storage was higher than 70℃ to make sure all the SAT inside the heat storage was in a liquid state. During the discharge tests, the inlet temperature of the heat transfer fluid was around 30℃ (T_c) all the time.

First the heat loss coefficient (*h*) of the heat storage was determined at a steady-state test with three different high inlet temperatures and low volume flow rate. Under steady-state conditions, the power transferred to the heat storage is equal to the heat loss of the heat storage. The heat loss coefficient (*h* [W/K]) can be calculated by $h = \frac{c_{pwater} \cdot \rho_{water} \cdot \dot{V} \cdot (T_{in} - T_{out})}{T_{surfave} - T_{ambient}}$

where c_{pwater}, ρ_{water}, $\dot{V}$ are the specific heat capacity [J/kgK], density [kg/m^3] and volume flow rate [m^3/s] of the heat transfer fluid, T_{in} and T_{out} are the inlet and outlet temperature of the heat transfer fluid, $T_{surfave}$ and $T_{ambient}$ are the average storage surface temperature and the ambient temperature [℃]. The measured heat loss coefficients of the heat storage appear from figure 10.

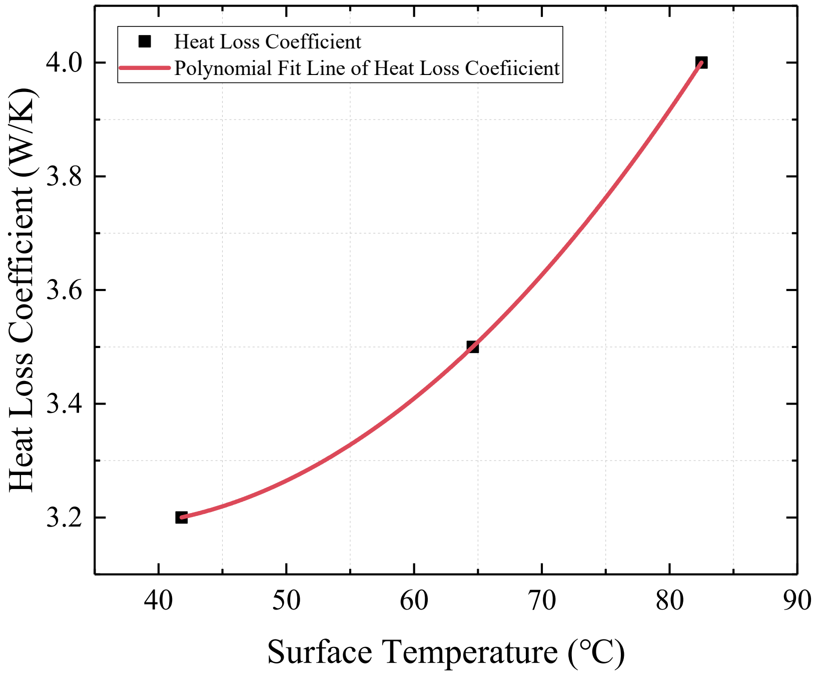


Fig. 10. Measured heat loss coefficients for different heat storage temperatures.

The heat content (*H*) of the heat storage was measured by means of a number of charge and discharge tests. The increase of heat content during a time step Δt of a charge test is determined by

$$\Delta H = ((c_{pwater} \cdot \rho_{water} \cdot \dot{V} \cdot (T_{in} - T_{out}) - h \cdot (T_{surface} - T_{ambient})) \cdot \Delta t$$

The decrease of heat content during a time step Δt of a discharge test is determined by

$$\Delta H = ((c_{pwater} \cdot \rho_{water} \cdot \dot{V} \cdot (T_{out} - T_{in}) + h \cdot (T_{surface} - T_{ambient})) \cdot \Delta t$$

The average heat storage temperature (T_{sto}) can not be measured directly. The average heat storage temperature is therefore calculated for each time step of the tests based on the heat content of the heat storage.

In periods where SAT is in solid state the following equation is used:

$$T_{sto} = H/(c_{p.sat.s} \cdot m_{sat} + c_{p.steel} \cdot m_{steel} + c_{p.water} \cdot m_{water})$$

In periods with SAT is in liquid state the following equation is used:

$$T_{sto} = T_m + ((H - H_{m2})/(c_{p.sat.l} \cdot m_{sat} + c_{p.steel} \cdot m_{steel} + c_{p.water} \cdot m_{water}))$$

In periods with SAT melting or solidifying $T_{sto} = T_m$.

$c_{p.sat.s}$ and $c_{p.sat.l}$ are the specific heat capacity of SAT in the solid and liquid state, m_{sat}, m_{steel} *and* m_{water} are the masses of SAT, stainless steel and water in the heat storage, $c_{p.steel}$ *and* $c_{p.water}$ are the specific heat capacity of stainless steel and water, T_m is the melting point of SAT, H_{m2} is the heat content of the heat storage in the supercooled liquid state at the initial cold heat storage temperature.

The heat exchange capacity rate (*HXCR*) [W/K] during charge and discharge periods is determined by the equation: $HXRC = -\,c_{pwater} \cdot \rho_{water} \cdot \dot{V} \cdot ln(1 - \frac{T_{in}-T_{out}}{T_{in}-T_{sto}})$

61 different heating/cooling cycle tests with different conditions have been carried out. The stability of the supercooling of the SAT was analyzed by the results of tests. The statistic results of the stability of the supercooling appear from table 2.

Flow rate [L/min]	Heating temperature [℃]	Heating duration [h]	Supercooled	Not supercooled	Probability of supercooling [%]
7	72	20	0	2	0
		7	0	2	0
7	77	20	3	1	75
		7	1	1	50
7	82	20	2	1	67
		7	2	1	67
7	87	20	3	2	60
		7	1	1	50
7	92	20	7	3	70
		7	7	4	64
6	92	20	4	1	80
5	92	20	4	2	67
3	92	20	4	2	67

Table 2. Number of tests with successful supercooling.

The tests were carried out with different volume flow rates, different durations of the heating period and different temperature levels at the end of the heating periods. With a temperature level at the end of the heating period of 72 ℃, supercooling will not occur. For temperature levels at the end of the heating period higher than 77°C the chance of supercooling is in the range of 50-80%, regardless of the test conditions. From the table it is further seen, that the chance of supercooling is increasing by increasing volume flow rate and increasing duration of the heating period. If both the heating temperature and the volume flow rate is high, the probability of supercooling is around 70%. It is therefore judged that the heat storage is suitable for long term heat storage.

The heat content of the heat storage was measured to be in good agreement with the theoretically calculated heat content of the heat storage based on masses of sodium acetate trihydrate, water and stainless steel of the heat storage and on literature values for specific heat capacities and heat of fusion. Figure 11 shows the measured and calculated heat content of the heat storage as a function of the average heat storage temperature.

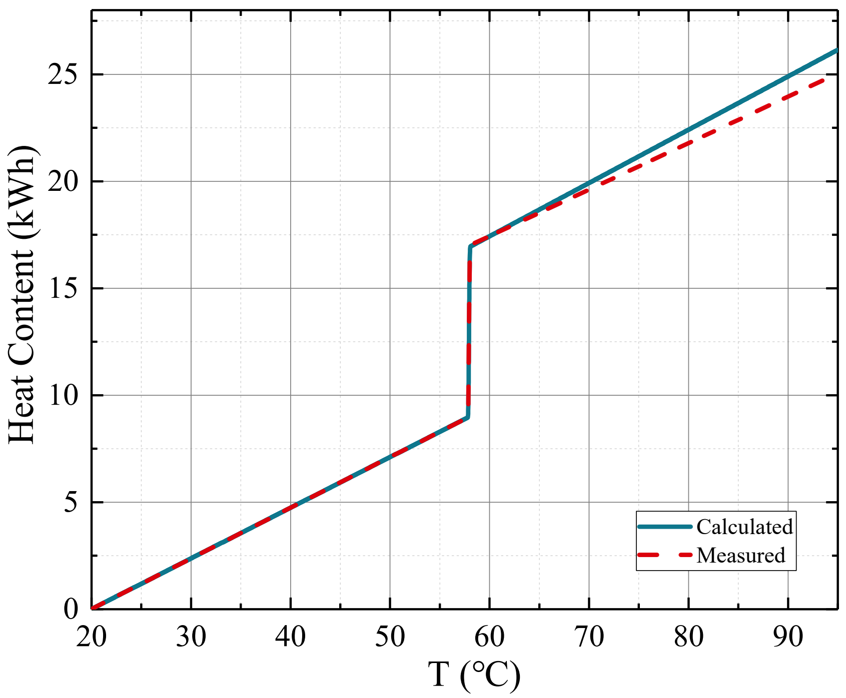


Fig. 11. Measured and calculated heat content of heat storage as a function of the average heat storage temperature.

It is from the tests also concluded that the long term stability of the heat storage is good. The heat content of the heat storage is not reduced during the tests.

The measured heat exchange capacity rate (HXCR) as a function of the average heat storage temperature during heating periods with different volume flow rates appear from figure 12. For increasing volume flow rate, the heat exchange capacity rate is increasing. The heat exchange capacity rate is relatively constant as long as the sodium acetate trihydrate is in the solid state, during melting the heat exchange capacity is strongly increased, and when the sodium acetate trihydrate is fully melted the power supply to the heat storage and consequently the heat exchange capacity rate is decreased. It is judged, that the heat exchange capacity rates are sufficiently high for most energy systems.

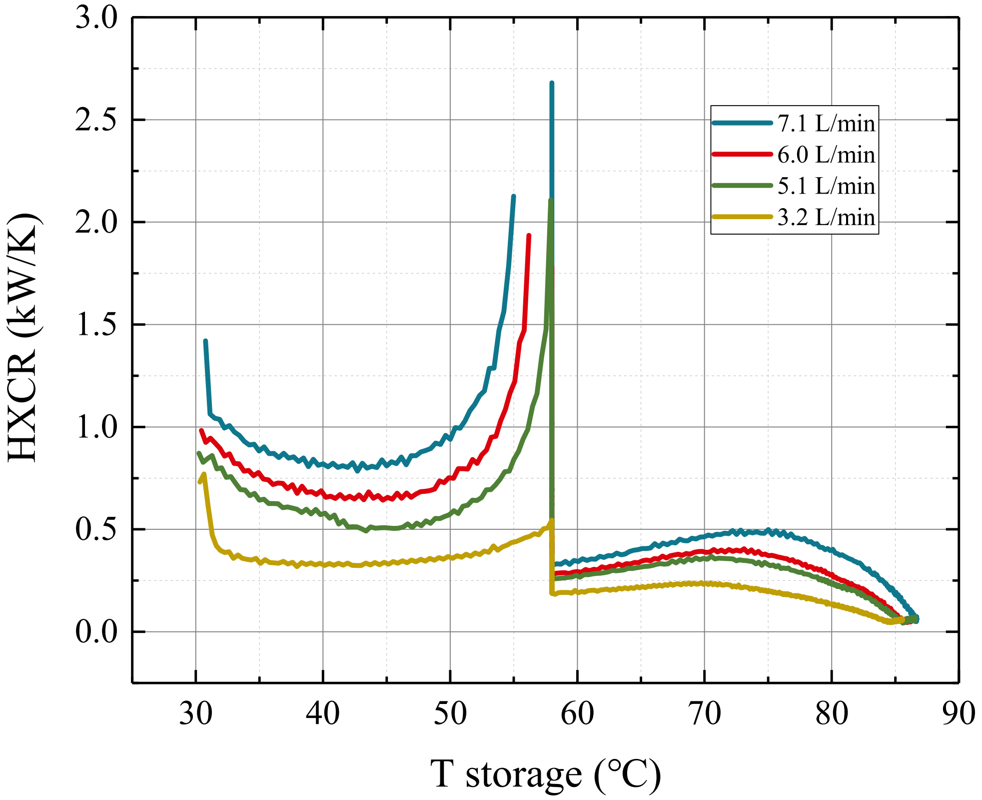


Fig. 12. Measured heat exchange capacity rate as a function of the average heat storage temperatures during heating periods with different volume flow rates.

The measured discharged power from the heat storage as function of the average heat storage temperature is shown in figure 13 for cooling periods with different volume flow rates. The inlet temperature for the heat transfer fluid was 30°C for all cooling periods. During all the cooling periods, the SAT is in the liquid state, that is the SAT is supercooled down to about 30°C. For increasing volume flow rate, the discharged power is increasing.

The measured discharged power from the heat storage as function of the average heat storage temperature is shown in figure 14 for cooling periods with solidification for different volume flow rates. The inlet temperature for the heat transfer fluid was 30°C for all these cooling periods. The cooling periods are started with solidification of the SAT. For increasing volume flow rate, the discharged power is increasing.

Based on the cooling tests of the heat storage it is judged, that the heat storage works as expected in a stable way.

Further, from the heating and cooling tests it is also concluded that the heat transfer rates to and from the heat storage are sufficient for typical applications in normal houses.

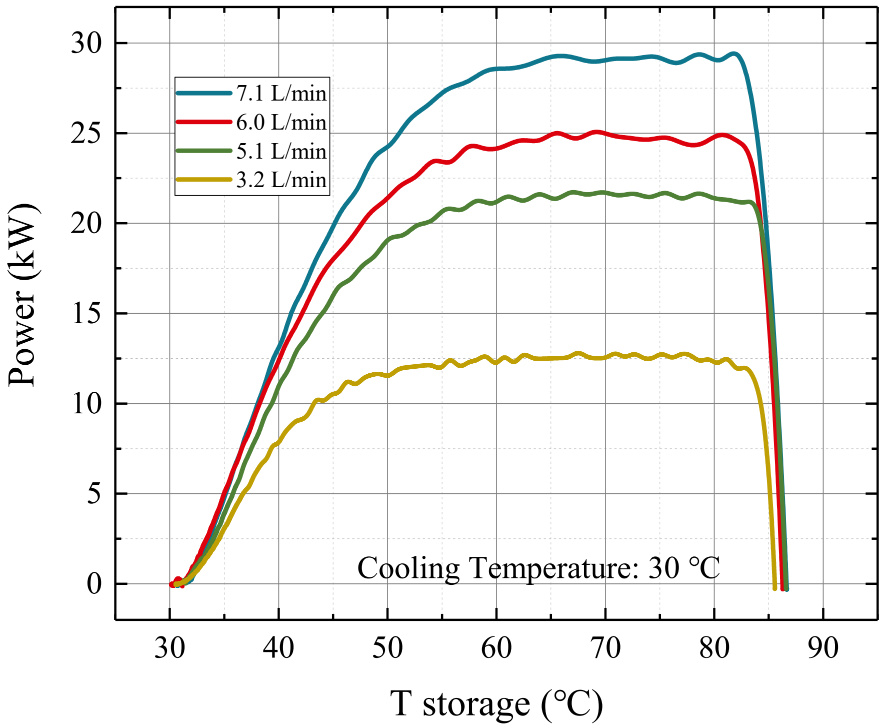


Fig. 13. Measured power discharged from the heat storage as function of the average heat storage temperature during cooling tests with supercooled SAT for different volume flow rates.

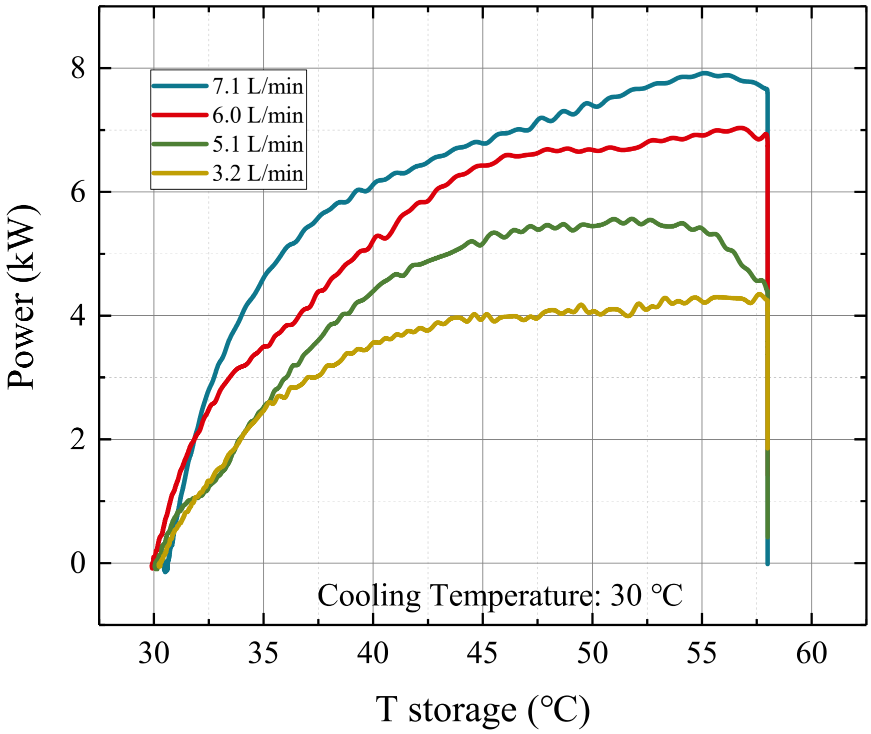


Figure 14. Measured power discharged from the heat storage as function of the average heat storage temperature during cooling tests without supercooling for different volume flow rates.

Further, parallel laboratory tests of 10 identically designed heat storage modules from H.M. Heizkörper have been carried out with the aim study the stability of the supercooling of the PCM in the modules and the long term stability of the modules, see figure 15. The heat storage modules consist of vertical cylindrical hot water tanks surrounded by mantles holding SAT with polymer additives. The results showed that the stability of the supercooling is influenced by the temperature used to discharge the modules. The lower the temperature is, the higher the risk of spontaneous crystallization will be. The tests showed that the supercooling is reliable under typical operation conditions. Further, the long term stability of the modules is good, since the heat contents of the heat storages were not reduced by time.

Fig. 15. Modules with PCM from H.M. Heizkörper tested in a laboratory test facility.

System simulation

A simulation model of a solar heating system with a PCM heat storage based on sodium acetate trihydrate with the ability to supercool and a hot water buffer tank was built in the TRNSYS 17 environment. The design of the solar heating system is the design of the solar heating tested at the laboratory test facility for solar heating systems at DTU Civil Engineering within the COMTES project. The PCM heat storage consisted of a number of separate modules. The water tank model (type 8893), the multiple flat PCM unit model (type 8888), the controller of PCM units (type 8889) and the system controller (type 8896) have been developed in a cooperation with the

Technical University of Graz. The system control strategy was implemented in type 8896. The collector array was modeled with type 538. Minute-based weather data from 2016, measured at the DTU climate station, was used for yearly system simulation. The yearly global radiation on a horizontal plane was measured to 1010 kWh/m^2, similar to the Danish reference year (1038 kWh/m^2).

Measurements from the solar heating system tested in the laboratory test facility were used for model validation. Table 3 shows measured and calculated energy quantities for the system. For the collector loop a period of 42 days was compared. For water tank charge, SH and DHW consumption as well as PCM charge and discharge, single days were analysed. There are good agreements between all measured and calculated quantities.

	Measurement (kWh)	**Simulation (kWh)**	**Deviation (kWh)**	**Deviation (%)**
Collector loop (March 17th – April 28th 2016)	1146	1168	22	1.9
Water tank charge	25.2	25.6	0.4	1.7
Space heating consumption	10.4	10.2	0.2	1.9
Hot water consumption	4.76	4.83	0.07	1.5
PCM unit charge	28.09	27.91	0.18	0.6
PCM unit discharge	8.87	9.09	0.23	2.6

Table 3: Simulated and measured heat transfer in collector loop, water tank and PCM heat storage.

Simulation results were evaluated by using yearly energy balances. They were calculated using periodic integration of heat transfer rates in the hydraulic circuits. The net utilized solar heat (Q_{solar}) resulted from the sum of the domestic hot water supply and the space heating demand minus the auxiliary energy: $Q_{solar}\ (kWh) = \int(\dot{Q}_{SH} + \dot{Q}_{DHW} - \dot{Q}_{auxiliary}) * dt$

The solar fraction (SF) of the solar heating system was determined by:

$$\boldsymbol{SF}\ (\%) = \mathbf{1} - \frac{\int(\dot{\boldsymbol{Q}}_{\boldsymbol{auxiliary}})*\boldsymbol{dt}}{\int(\dot{\boldsymbol{Q}}_{\boldsymbol{SH}}+\dot{\boldsymbol{Q}}_{\boldsymbol{DHW}})*\boldsymbol{dt}} * \mathbf{100.}$$

Calculations with differently sized solar heating systems were carried out with the validated simulation model. The reference solar heating system consisted of 16 m² solar collectors with a tilt of 70°, a 1 m^3 PCM heat storage with 200 L PCM units with thermal insulation and a 600 L hot water buffer tank. A daily DHW consumption of 130 L at 45 °C corresponding to 5.175 kWh per day was applied. A yearly space heating demand of 2088 kWh was assumed, resulting in a total yearly heat demand for space heating and domestic hot water supply of 3977 kWh.

Figure 17 shows how the solar fraction is changed by changes of the solar collector area, the solar collector tilt, the PCM unit volume, the PCM heat storage volume and whether or not the PCM heat storage is fully charged by electrical heating January 1 due to assumed low cost electricity in a windy period.

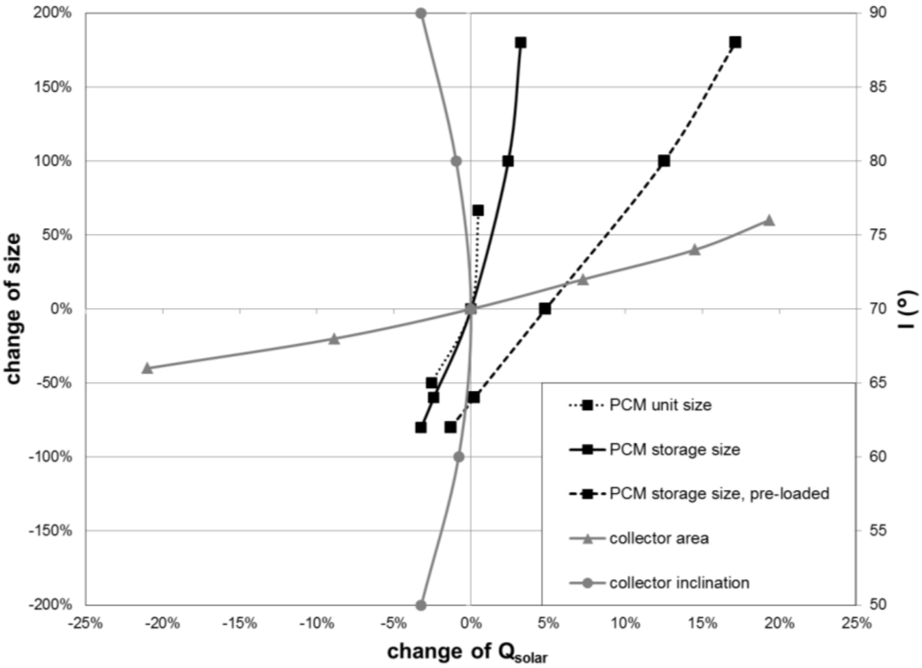


Fig. 17. Yearly net utilized solar heat in dependency of PCM heat storage and collector array parameters

PCM units of 200 L were found to perform better than units of 150 L. The optimal solar collector array tilt was determined to be 70°. Collector array sizing had the highest impact on Q_{solar}, where relative changes of +/– 20% were calculated with a 60% larger and respectively 40% smaller collector area. Relatively small changes of Q_{solar} (+/– 3%) were determined for PCM heat storage sizes 180% larger and 80% smaller. Assuming full storage charge at the beginning of the year, Q_{solar} would be 5% higher with V_{PCM}=1 m^3 and 14% higher with V_{PCM} =2.8 m^3, respectively.

Table 4 presents the influences of the collector area, the PCM volume (200 L units) and the water tank volume on the yearly SF. SF ranged from 47.5% (V_{water}=0.6 m^3, A=9.6 m^2; V_{PCM}=0.2 m^3) to 76.7% (V_{water}=1 m^3, A=25.6 m^2; V_{PCM}=2.8 m^3). SF changed moderately (about 4%) by variation of V_{PCM}. Collector area increase from A=9.6 m^2 to A=25.6 m^2 increased SF by approximately 25% points throughout all storage sizes. The performance difference was most pronounced between A=9.6 m^2 and A=12.8 m^2, respectively.

V_{PCM} (m^3)	**0.2**	**0.4**	**1**	**2**	**2.8**
No. of units	**1**	**2**	**5**	**10**	**14**
A (m^2)	SF (%) with 0.6 m^3 water				
9.6	47.5	47.9	49.1	50.3	50.3
12.8	54.8	55.2	56.5	57.8	59.3
16	60.2	60.4	62.2	63.7	64.3
19.2	64.8	64.8	66.2	67.7	68.5
22.4	68.9	68.9	71.2	72	72.7
25.6	72.7	73.8	74.2	75.1	76.1

Table 4: Parametric study on yearly SF.

The system was found to perform best with collector areas between 12.8 and 22.4 m^2, with $V_{PCM} < 1\ m^3$ and when additional storage charge at the beginning of the year was assumed. With A=22.4 m^2, approximately 1000 kWh heat demand would be covered by 1 m^3 SAT composite and its heat storage capacity would be utilized 5.5 times per year, those of the water tank 116 times per year respectively.

Full-charge of a single 200 L PCM unit and a 0.6 m^3 water tank enabled heat supply of 2 days in January, which increased to 18 days when 2.8 m^3 of SAT composite was charged. The heat storage of the system could be charged several times during winter in periods with surplus of wind energy and in summer, spring and autumn by solar collectors.

As presented in Figure 18, the system could reveal a SF of 71% and additionally utilize wind power generation peaks in winter, whereas only a relatively small storage volume would be required.

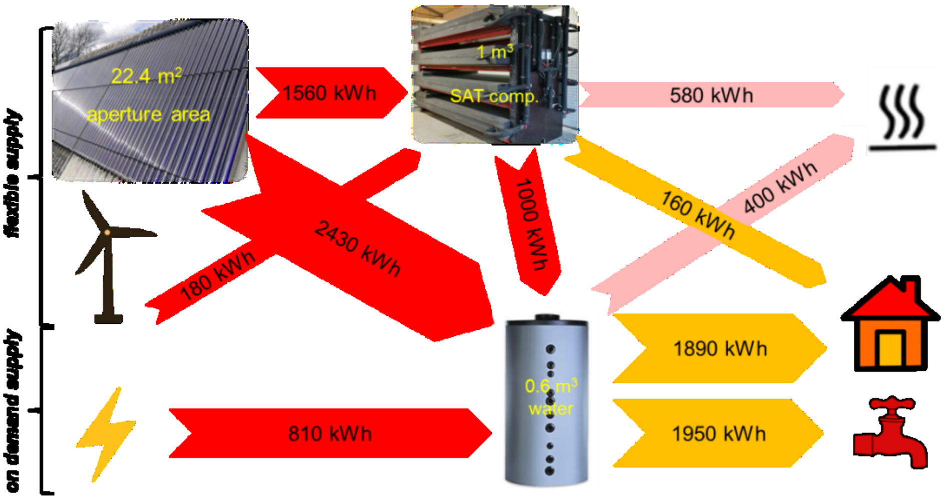


Fig. 18: Yearly heat flux scenario (supply in red, demand in orange, heat loss in pink) with a SF of 71%.

From the project it is concluded that SAT with additives can work as long term stable heat storage materials with reliable supercooling and sufficiently high heat exchange capacity rates in inexpensive heat storages. The heat storages can be used both as short term and long term heat storages. The heat storages work as short term heat storages relying on the specific heat of SAT in the liquid state, that is the heat storage can be operated without SAT in solid state. The heat storage can work as a long term heat storage where solidification of the SAT is used after long periods with the SAT in the liquid phase at the ambient temperature.

The investigations further showed, that solar heating systems with combined short and long term PCM heat storages can cover a high part of the yearly heat demand of buildings in Denmark. In the future it is expected that there in winter periods will be days with low cost electricity. Low cost electricity can be used to charge the PCM heat storages during winter. In this way the thermal performance of the combined solar heating/wind energy systems with combined short and long term PCM heat storages can cover almost all the yearly heat demand of buildings without high requirements on the heat storage volume.

Furthermore, a simulation model of a heat pump system with a PCM heat storage tank consisting both of PCM material and water inclusive a heat exchanger for domestic hot water preparation was developed in the TRNSYS 17 environment. The PCM heat storage (type 5850) and the control component (type 5894) was developed and the heat pump (type 9410) was modified from the TESS component type 941. The PCM heat storage (type 5850) was validated by tests carried out at DTU Civil Engineering. The energy balance of the whole simulation model was verified under different conditions.

The simulation model simulate a heat pump system with PCM heat storage covering all the yearly DHW consumption and Space heating demand for a typical Danish house under typical Danish weather conditions. The house temperature was targeted between 19°C and 21°C during winter period. A daily DHW consumption of 4.5 kWh is assumed. The PCM heat storage volume is 400 L. The electricity price is assumed to be the Danish floating electricity price of 2018. The auxiliary heater set point temperature is 55 °C. The heat storage volume (PCM volume VOLpcm and water volume VOLwater), the PCM melting point, the Heat Exchange Capacity Rate between PCM and water (HXCR) and different control strategies (basic and smart) were studied as varying parameters in different cases. The electric energy used by the heat pump (HPenergy), the heat pump heat output (HPheat), the DHW consumption (DHW), the space heating demand, the auxiliary power (Aux), the average COP and the electricity cost were calculated. The parameter settings and the results can be found in tables 5 and 6. Basic control means the controller will only send control signals based on the DHW consumption, the space heating demand and the energy status of the PCM heat storage. The smart control will consider further on day and night charge, floating electricity price, method of increasing COP and user defined non-charging period. Night charge means the heat pump only charge the heat storage at night. Qmax defines the maximum energy of charging heat storage.

Case	VOLwater	VOLpcm	Melting point	Latent heat	HXCR	Control
-	m^3	m^3	°C	kJ/kg	W/K	-
1	0.1	0.3	58	265	500	basic
2	0.2	0.2	58	265	500	basic
3	0.3	0.1	58	265	500	basic
4	0.3	0.1	58	265	250	basic
5	0.3	0.1	50	265	500	basic
6	0.3	0.1	50	265	500	Smart
7	0.3	0.1	50	265	500	Smart+night charge
8	0.3	0.1	50	265	500	Smart+night charge+Qmax
9	0.1	0.3	50	265	500	Smart+night charge
10	0.1	0.3	58	265	500	Smart+night charge

Table 5: Parameter settings in case studies

Case	HPenergy	COP	Cost
-	kWh	-	DKK
1	10111	2.5	3075
2	9542	2.6	2900
3	8891	2.7	2681
4	9329	2.7	2821
5	7774	2.7	2323
6	7805	2.8	2279
7	7824	2.9	2253
8	7710	2.9	2248
9	8465	2.8	2314
10	9371	2.7	2581

Table 6: Simulation results of case studies

It can be concluded from the tables that:

- A melting point of 50°C is better than a melting point of 58°C
- Increased water volume and higher HXCR reduce the energy consumption and cost under basic control
- Using smart control increase the heat pump COP
- Using smart control will reduce the yearly total cost up to 27%

The project results form a basis for further research and development on economically attractive energy systems with combined short and long term heat storages. It is expected that such heat storages will be important in the future energy system with many different renewables. Therefore an increased turnover and an increased number of employed in the field is expected in the future.

The project results were disseminated by the following presentations and publications:
Heat storage meeting at The Danish Academy of Technical Sciences (ATV), March 28, 2017. Simon Furbo: Presentation: "Langtidsvarmelagring baseret på salthydrater (Long term heat storage based on salt hydrates)".
DANVAK DAGEN 2017, Copenhagen, April 5, 2017. Mark Dannemand: Presentation: "Udvikling af langtidsvarmelager til solvarmeanlæg i enfamiliehuse (Development of long term heat storage for solar heating systems in single family houses)".
Workshop at Engineers Union IDA Odense, Denmark, May 30, 2017. Mark Dannemand: Presentation: "Gem sommerens varme i flydende salt (Save heat from the summer in liquid salt)".
Youth for Understanding Denmark's (YFU) Sustainable Energy Programme Summer School at DTU, Denmark, June 15, 2017. Gerald Englmair: Presentation: "Heat storage by supercooled Phase Change Material (PCM)".
Heat storage workshop at North China Electric Power University (NCEPU), School of Energy Power and Mechanical Engineering. Gerald Englmair: Presentation: "Long-term PCM heat storage based on stable supercooling of Sodium Acetate Trihydrate (SAT)".
12th International conference on Buildings and Environment "enviBuild 2017", Technical University of Vienna, Austria, September 7-8, 2017. Conference paper: Christoph Moser, Gerald Englmair, Hermann Schranzhofer, Andreas Heinz: "Simulation Study of a Novel Solar Thermal Seasonal Heat Storage System based on Stable Supercooled PCM for Space Heating and Domestic Hot Water Supply of Single Family Houses".
Sino-Danish Center for Research and Education workshop at University of Chinese Academy of Sciences, Yanqihu Campus, China, September 24, 2017. Gerald Englmair: Poster presentation: "Sustainable energy system: Long-term PCM heat storage for a solar space heating and domestic hot water combisystem".
ISES Solar World Congress (SWC 2017) & IEA Solar Heating and Cooling Programme´s SHC 2017 conference, Abu Dhabi, United Arabian Emirates, October 29 - November 2, 2017. Gerald Englmair: Presentation: "Performance Evaluation of a Demonstration System with PCM for Seasonal Heat Storage: Charge with Evacuated Tubular Collectors".
"Performance Evaluation of a Demonstration System with PCM for Seasonal Heat Storage: Charge with Evacuated Tubular Collectors." Proceedings of the ISES Solar World Congress (SWC) 2017 conference in Abu Dhabi, United Arabian Emirates,. Englmair, G., Furbo S., Kong, W., Dannemand, M., Fan, J., Wang, Z..
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"Update: Research on heat storage using sodium acetate trihydrate with and without stable supercooling." Presentation at the IEA task 58/ Annex 33; 3rd expert meeting in Ljubljana. 9-11 April 2018. Gerald Englmair.

"Supercooling stability of sodium acetate trihydrate composites in multiple heat storage units." Presentation at PCM2018 conference, Orford (QC), Canada. 21 – 23 May 2018. Dannemand M.

"Crystallization by local cooling of supercooled sodium acetate trihydrate composites for long-term heat storage." Energy and Buildings. Englmair, G., Jiang, Y., Dannemand, M., Moser, C., Schranzhofer, H., Furbo, S., Fan, J. (2018).

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"Combined short- and long-term heat storage with Sodium Acetate Trihydrate in cylindrical tanks." Presentation at EuroSun 2018 - 12th International Conference on Solar Energy for Buildings and Industry, Rapperswil, Switzerland, September 10-13, 2018. Englmair, G., Furbo, S., Dannemand, M., Fan, J.

"PCM solutions for energy storage." CITIES 5th General Consortium Meeting Fredericia, Denmark. September 20-21, 2018. Presentation by Dannemand, M.

"Combined short- and long-term heat storage for solar heating systems." Presentation at the 2nd Alumni seminar on sustainable energy, DTU, Denmark, September 28, 2018. Englmair, G.

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"Combined short and long-term heat storage with sodium acetate trihydrate for solar combi-systems." G. Englmair. PhD Thesis. Department of Civil Engineering, Technical University of Denmark, 2019.

Newsletter article in Solar Update, Vol. 69, 2019, pp. 14-15: "Combining Short and Long-Term Heat Storage for Solar Heating Systems." Gerald Englmair, Simon Furbo, Mark Dannemand.

1.6 Utilization of project results

The project results form an excellent basis for further research and development on economically attractive energy systems with combined short and long term heat storages. An ongoing research project carried out in a cooperation between Department of Civil Engineering, Technical University of Denmark and H.M.Heizkörper and a EU research project, ComBioTES, recently approved by EU have focus on further development of the improved compact short and long term heat storages. Both the Technical University of Denmark and H.M. Heizköper are participating in the ComBioTES project.

Further, in an ongoing EUDP project Suntherm ApS has focus on development and demonstration of heat pump systems with compact PCM heat storages.

Based on the above mentioned an increased turnover and an increased number of employed in the field is expected in the future.

Economically attractive energy systems with combined short and long term heat storages are expected to be important parts of our future energy system based on different renewable energy systems with time differences between energy productions and heat demands.

No patents have been taken out within the project.

A PhD study was partly financed by the project. The project results were also tought to students at the Technical University of Denmark following courses on solar energy and energy storage.

1.7 Project conclusion and perspective

The project showed that PCM heat storages with stable supercooling can work in a reliable way as compact combined short and long term heat storages, and that combined short and long term PCM heat storages are suitable for future solar heating systems where the heat storage can be charged both with solar heat and cheap electricity in windy winter periods.

The project results form an excellent basis for future development of economically attractive energy systems with combined short and long term heat storage. Such heat storages are expected to be important elements of the future energy system relying on different renewable energy systems with fluctuating energy production.

Annex

Homepage for IEA SHC Programme Task 58 project: http://task58.iea-shc.org/.

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