# System Simulation Report
# System: PCM with supercooling

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

## Report C6.2 of Subtask C

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Task 32
Storage

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Report on System Simulation

C6.2: Appendix 2 of report C6

# PCM with supercooling

by

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A technical report of Subtask C

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## Content

# 1 General description of PCM system with supercooling

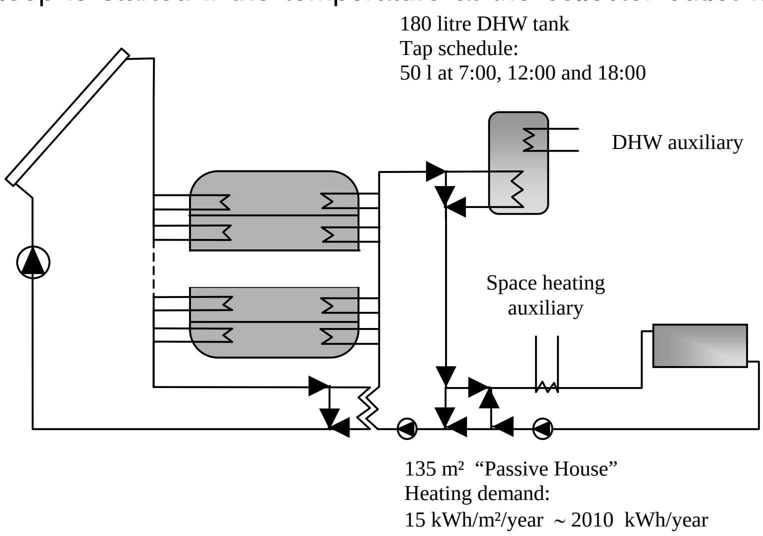
### Main features

The system is designed for 100% coverage by solar of both domestic hot water (DHW) and space heating in a low energy single family house according to the passive house standard. This is achieved by means of a seasonal phase change material (PCM) storage combined with a small DHW tank. The phase change material is sodium acetate tri-hydrate with a melting point of 58°C and the ability of stable supercooling. The PCM storage is subdivided into several sub-volumes. The system benefits from the supercooling as the PCM when melted can cool down, e.g. due to heat loss, to surrounding temperature in its liquid phase preserving the energy related to the heat of fusion. When a storage sub-volume has reached the surrounding temperature this part of the storage is heat loss free. As soon as there is a need for heating that cannot be covered directly from the collector or from a liquid or solidified sub-volume the solidification in a supercooled sub-volume is activated in which case the heat of fusion energy is released and becomes usable for DHW and/or space heating. The DHW tank is required to meet the power demand during hot water draw offs. The heating system is a low temperature system, i.e. floor heating or radiators.

### Heat management philosophy

Solar collector loop:

The pump in the solar collector loop is started if the temperature at the collector outlet is higher than either the minimum temperature of all sub-volumes in the PCM-storage or the minimum temperature in the DHW-tank or in case of space heating demand the return temperature from the space heating loop.




When the pump in the solar collector loop is running the highest priority is on covering the space heating demand. Second priority is to heat up the DHW-tank until the set-point of 55°C has been reached. Third priority is to charge the seasonal PCM-storage. The strategy for charging of the PCM storage sub-volumes is to charge one sub-volume at the time until fully melted. In case the outlet temperature of the solar collector is lower than the melting point one sub-volume at the time is heated to the maximum obtainable temperature under the actual conditions. When all sub-volumes has been melted the DHW-tank is further heated until 70°C, where after the PCM-storage is charged.

The pump stops either when the collector outlet temperature is lower than the minimum of the PCM storage sub-volume temperature, the minimum DHW-tank temperature and the space heating return temperature or when the DHW-tank has reached a temperature of 70°C and all sub-volumes in the PCM-storage has reached a temperature of 95°C.

Demand loop:

If possible the DHW-tank and/or the space heating loop are heated directly by the solar collector loop through the heat exchanger connecting the solar collector loop and the demand loop. In case the demand cannot be fulfilled by the collector loop the PCM-storage is discharged. The discharge strategy is first to discharge a liquid sub-volume that has a temperature just high enough to cover the demand temperature. Next a solidified sub-section with a sufficient temperature is discharged. Finally, the solidification is activated in a supercooled sub-section and discharged. The DHW-tank is always heated to the set-point temperature of 55°C.

Auxiliary energy:

The solar heating system is designed for 100% coverage by solar of DHW and space heating so in principle auxiliary energy is not needed. However, if required auxiliary energy is supplied by electric heating elements in the DHW-tank and in the space heating loop.

## Influence of auxiliary energy source on system design and dimensioning

Auxiliary energy will only be needed in rare cases, i.e. in case of extremely bad summers or extremely hard winters or in case of malfunctioning of the system.

## Cost (range) and market distribution

The described design has not been tested yet.

# 2 Modelling of the system

The system has not been modelled using the reference template, but parametric studies have been carried out in TRNSYS 15 with the model described below. The simulations have been performed with the main goal to evaluate the potential of the concept. As a consequence no effort has been put into simulating details such as heat loss from pipes, and the PCM storage is also treated as a perfect working storage only considering heat losses to the surroundings.

## 2.1 TRNSYS model

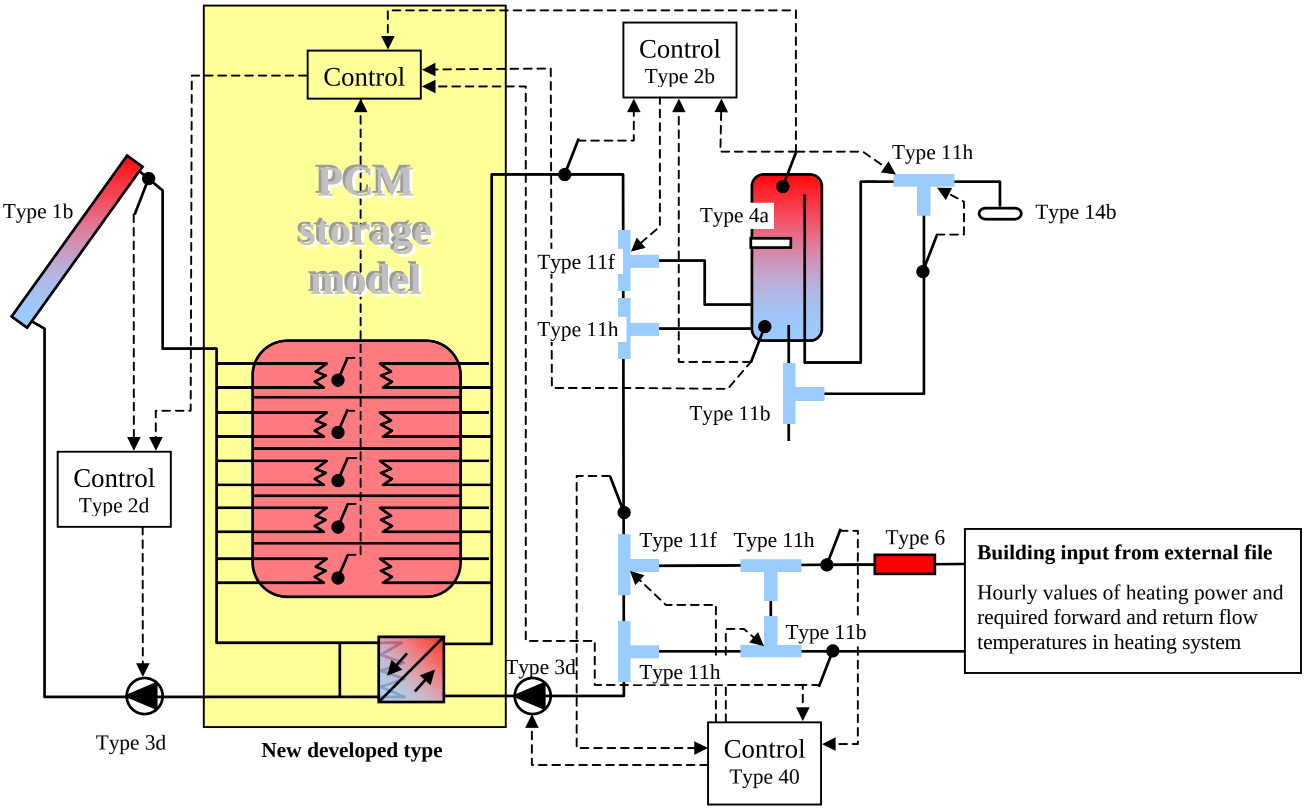



**Figure 1.** Modelling of the system “PCM with supercooling” in TRNSYS 15.

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

### 2.2.1 General Settings

***General Settings:***

| ***Main*** | |
|---|---|
| simulation time step | 0.01 h |
| tolerance integration / convergence | 0.01 / 0.001 |
| length of simulation | 24 months |
| climate | Copenhagen |
| building | Passive house standard<br>15 kWh/m$^2$/year = 2015 kWh/year |
| ***Auxiliary (electrically) in DHW tank*** | |

| | |
|---|---|
| Nominal Power of Auxiliary | 4320 kJ/h |
| Set temperature Auxiliary into store | 55°C |
| Auxiliary temperature rise | 4 K |
| ***Auxiliary (electrically) in space heating*** | |
| Nominal Power of Auxiliary | 15000 kJ/h |
| Set temperature Auxiliary into store | Depends on heating load |
| Auxiliary temperature rise | - |
| ***Collector*** | |
| type | flat plate selective (ref) |
| aperture area | 36 $m^2$ |
| tilt angle | 75° |
| azimuth (0° = south, 90° = west, 270° east) | 0° |
| primary loop specific mass flow rate | 50 $kg/h/m^2$ |
| upper / lower dead band (switch on / off) | 5 K / 1 K |
| cut-off temperature of collector | PCM-store > 95°C and DHW-tank > 70°C |
| ***DHW-store*** | |
| storage volume | 0.18 $m^3$ |
| effective heat loss coefficient | 0.83 $W/m^2K$ |
| ***PCM-store*** | |
| storage volume | 10 $m^3$ |
| effective heat loss coefficient | 0.6 $W/m^2K$ |

### 2.2.2 Collector

Type: 1b Version Number:

| | | |
|---|---|---|
| Collector | $\eta_0$ | 0.82 - |
| | $a_1$ | 2.44 W/m²-K |
| | $a_2$ | 0.005 W/m²-K² |
| | 1st order IAM | 0.135 |
| | 2nd order IAM | -0.006 |
| | Area | 36 m² |
| | Specific mass flow | 50 l/m²/h |

### 2.2.3 Heat exchange in the collector loop

Heat exchange takes place either in the PCM storage, in the heat exchanger between the collector loop and the demand loop or both.

- The heat exchange in each PCM-storage sub-volume is simulated as a constant heat transfer coefficient of 500 W/K.
- The heat exchanger between the collector loop and the demand loop is simulated based on values from a specific plate heat exchanger as:

| | |
|---|---|
| Heat exchanger area m² | 0.6 m² |
| Heat transfer coefficient primary side: | $10700 \times \left(\dot{q}_{primary}\right)^{0.84}$ $W/m^2K$, $\dot{q}_{primary}$ = primary flow (l/s) |
| Heat transfer coefficient secondary side: | $10700 \times \left(\dot{q}_{secondary}\right)^{0.84}$ $W/m^2K$, $\dot{q}_{secondary}$ = secondary flow (l/s) |

The approximate heat transfer coefficient in the heat exchanger with the flow rates appearing in the simulations is 800 W/K.

The heat exchange in the PCM storage as well as the heat exchanger between the collector loop and the demand loop is included in the developed PCM storage TRNSYS type.

### 2.2.4 Pipes between Collector and Storage:

**NOT MODELLED.**

### 2.2.5 Control of the collector loop

The collector loop is controlled by a combined evaluation of the temperatures in the PCM storage, the DHW-storage and the required supply temperature in the space heating loop. The combined governing temperature is an output from the PCM storage TRNSYS type that goes to the controller (St-coll).

Type 2

| ***Reason*** | ***Sensor*** | ***Off-Criteria*** | ***Hyst.*** |
|---|---|---|---|
| Upper dead beand (Udb) | Collector temperature (T-coll) and storage collector control (St-coll) | On: T-coll>st-coll + Udb | |
| Lower dead band (Ldb) | Collector temperature (T-coll) and storage collector control (St-coll) | Off: T-coll>st-coll + Ldb | |
| Storage tank protection | Combined storage collector control temperature (St-coll) | Cut off if: T-DHW > 70°C and T-PCM > 95°C and no space heating demand | 5 K |

### 2.2.6 PCM storage:

Type: New developed type Version Number:

| | | |
|---|---|---|
| Storage tank | Total volume | 10 m³ |
| | Height | 2.50 m |
| | Diameter | 2.50 m |
| | Store volume for auxiliary | None |
| | Number of nodes (sub-volumes) | 40 |
| | Media: | Sodium acetate tri-hydrate with active use of super cooling |
| | Effective heat loss coefficient | 0.6 W/m$^2$K |
| | Heat exchange collector loop – storage sub-volume | 500 W/K |
| | Heat exchange demand loop – storage sub-volume | 500 W/K |

The developed type is further described in Appendix 1.

### 2.2.7 Building

The building is a 135 m$^2$ detached single family low energy house with an annual energy consumption for space heating equal to 15 kWh/m$^2$/year according to passive house standard. The house has been simulated with the Danish building simulation tool tsbi3 and the output of the hourly space heating demand has been used as input for the TRNSYS simulations.

### 2.2.8 Heat distribution

The heat is distributed by a floor heating system or a low-temperature radiator heating system. The required supply temperature is calculated on hourly basis from the required power input the flow rate in the heating system (120 kg/hr) and a fixed return temperature in the heating system of 25°C.
The heating system is assumed to have an efficiency of 100%, i.e. no pipe losses.

### 2.2.9 Draw-Off loop

Hot water is tapped 3 times a day at a temperature of 50°C. The cold fresh water temperature is assumed constant at 10°C. A hot water consumption of 150 litres/day is assumed.

## 2.3 Validation of the system model

The investigated solar heating system has not been built and tested so no system model validation has been possible.

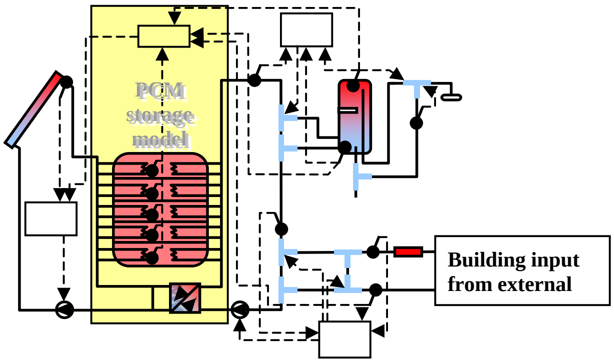
# 3 Simulations for testing the library and the accuracy

The accuracy of the simulations is checked by setting up the energy balance for the total system as well as for the PCM storage component and the DHW-tank. The energy balances have been used for determination of the best combination of time step (0.01 h) and integration and convergence tolerances: 0.01 and 0.001.

The main difficulties were related to the supercooling in the PCM-storage model or rather the activation of a supercooled sub-section, which is a discrete function: either the sub-section is at a low temperature of approximately 25 – 35°C or, if activated, at a temperature of 58°C. In several time steps such a sub-section will change between the two states from iteration to iteration leading to no convergence. The first attempt is in analogy to the on/off controllers to introduce a maximum number of oscillations where after the actual state of the sub-section is frozen, but the result were large energy imbalances. The final solution was still to operate with a maximum number of oscillations, but instead of freezing the state of the sub-section after the number of oscillations, the output temperatures from the storage model are averaged over the following iterations. After a few more iterations in the time step the simulation is converging. When the actual output temperature from the PCM-storage model is replaced with an average value of the previous iterations and the present an error in the energy balance is introduced. Therefore it became necessary to compensate for this in each iteration by changing the energy content in the storage accordingly. The result is a system energy balance below 10 kWh/year, which corresponds to approximately 0.05 % of the total annual energy flow.

# 4 Sensitivity Analysis and Optimization

## 4.1 Presentation of results




System: Seasonal PCM storage with active use of supercooling

| Main parameters (optimised Base Case (BC)): | | | |
|---|---|---|---|
| Building: | *Passive house* | Storage Volume: | *PCM 10 $m^3$*<br>*DHW 0.18 $m^3$* |
| Climate: | *Copenhagen* | Storage height | *2.5 m* |
| Collectors area: | *36 $m^2$* | Position of heat exchangers | *N/A* |
| Collector type: | *Flat Plate* | Position of in/outlets | *N/A* |
| Specific flow rate (Collector) | *50 kg/m²-h* | Thermal insulation | *0.6 $W/m^2K$* |
| Collector azimuth/tilt angle | *0 / 75°* | Nominal auxiliary heating rate | *PCM: None*<br>*DHW: 4320 kJ/h*<br>*Sp.heat: 15000 kJ/h* |
| Collector upper dead band | *5 °K* | Heat Exchanger: | *PCM: 500 W/K*<br>*Solar/demand 800 W/K* |
| Simulation parameter: | | Storage nodes | *PCM: 40 (sub-sections)*<br>*DHW: 8* |
| Time step | *1/100 h* | Tolerances Integration Convergence | *0.010/0.001* |

The primary objective for the parametric studies has been to investigate the influence of different parameters on the required PCM-storage volume that will result in 100 % solar fraction. As the PCM-storage is expected to be the most costly part of the solar heating system focus has been on ways to reduce the necessary PCM-storage volume.

| Summary of Sensitivity Parameters | | | |
|---|---|---|---|
| Parameter | Variation | [1]Variation in solar fraction | |
| Base Case (BC) | - | 100% | |
| Collector size [$m^2$] and PCM storage volume [$m^3$]<br>(fixed subsection volume = 100 litres) | 18 – 36 $m^2$<br>1 – 23 $m^3$ | 70 – 100% | Figure 2 |
| Sub-section and PCM storage volume [$m^3$]<br>(fixed collector area: 36 $m^2$) | 0.1 – 1.0 $m^3$<br>1 – 13 $m^3$ | 83 – 100% | Figure 3 |
| Effective heat loss coefficient [$W/m^2K$]<br>PCM storage heat loss usable/not usable<br>(fixed collector area 36 $m^2$) | 0.20 – 1.00 | 100% | Figure 4 |
| PCM volume vs. water storage volume [$m^3$]<br>(fixed collector area: 36 $m^2$) | 1 – 20 $m^3$ | 78 - 100% | Figure 5 |

**[1] The variation if fractional savings indicated in the table does not represent the values for the extremes of the range, rather the minimum and maximum values for the range indicated.**

| Sensitivity parameter: | Collector size [$m^2$] and PCM storage volume [$m^3$]<br>(fixed subsection volume = 100 litres) | 18 – 36 m2<br>1 – 23 m3 |
|---|---|---|

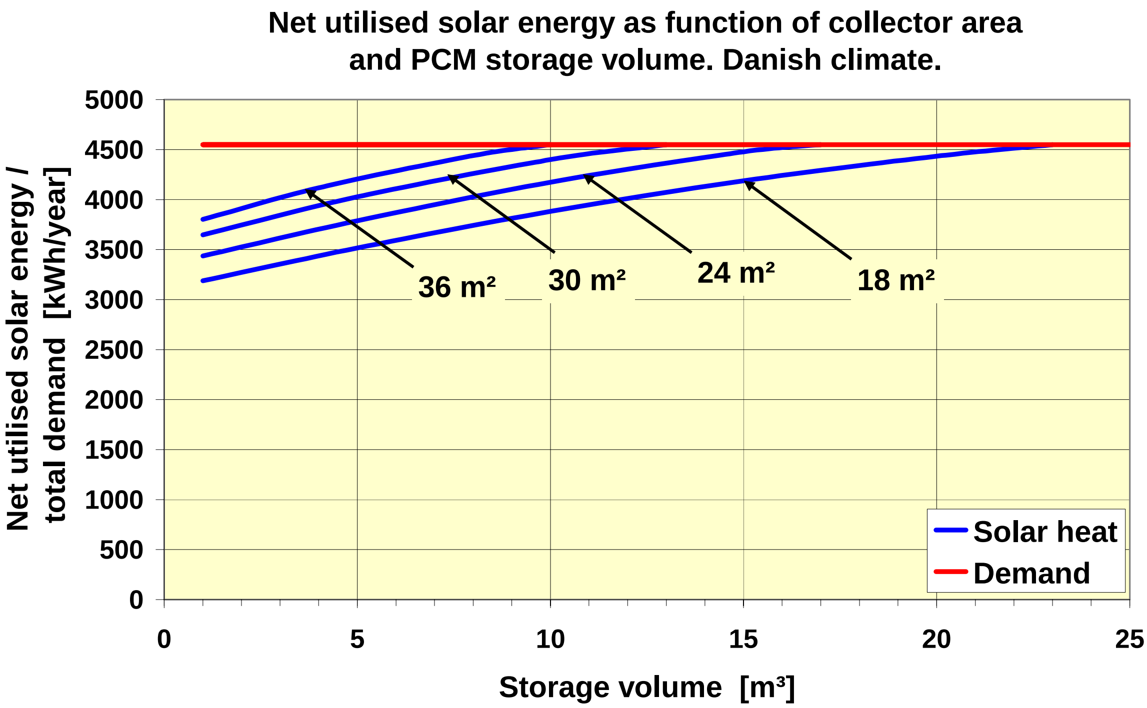



**Figure 2.** Net utilised solar energy as function of collector area and PCM storage volume. The red horizontal line indicates the total energy demand for both domestic hot water and space heating.

**Differences from Base Case (BC)**
The subsection volume has in this parametric study been set to 0.1 $m^3$ independent of the total PCM-storage volume, while the sub-section volume in the base case is 0.25 $m^3$.

**Description of Results**
The results show that an increase of the solar collector area from 18 – 36 $m^2$ results in a decrease in the required PCM-storage volume for 100 % solar fraction from 23 – 10 $m^3$. The optimum combination of solar collector area and PCM-storage volume will depend on an economical analysis.

**Comments**
None

| Sensitivity parameter: | Sub-section and PCM storage volume [m$^3$]<br>(fixed collector area: 36 m$^2$) | 0.1 – 1.0 m$^3$<br>1 – 13 m$^3$ |
|---|---|---|

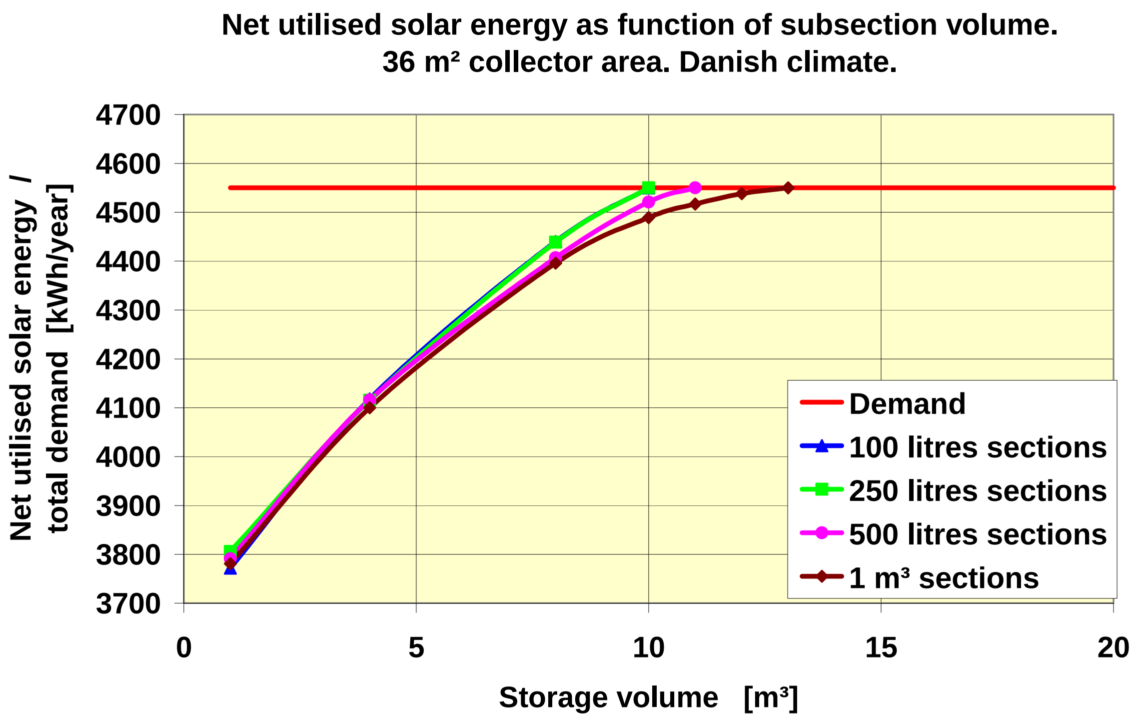



**Figure 3.** Net utilised solar energy as function of sub-sectionand total PCM storage volume. The red horizontal line indicates the total energy demand for both domestic hot water and space heating.

**Differences from Base Case (BC)**
Except for the parameters that are varied the model confirms with the base case.

**Description of Results**
The sub-section volume was expected to have an important influence on the PCM storage performance as many small volumes should make it easier to get a good match between the actual demand and the supercooled volume that have to be activated to cover the demand. However, the analysis shows that there is no difference in performance between sub-section volumes of 0.1 and 0.25 m$^3$. An increase of the sub-section volume to 0.5 m$^3$ influences the PCM-storage performance as the required total storage volume for 100% solar fraction increases from 10 m$^3$ to approximately 12 m$^3$ and further increase in sub-section volume to 1 m$^3$ increases the required total volume to approximately 14 m$^3$.

**Comments**
None

| **Sensitivity parameter:** | Effective heat loss coefficient [W/m²K]<br>PCM storage heat loss usable/not usable<br>(fixed collector area 36 m²) | 0.2 – 1.0 W/m²K |
|---|---|---|

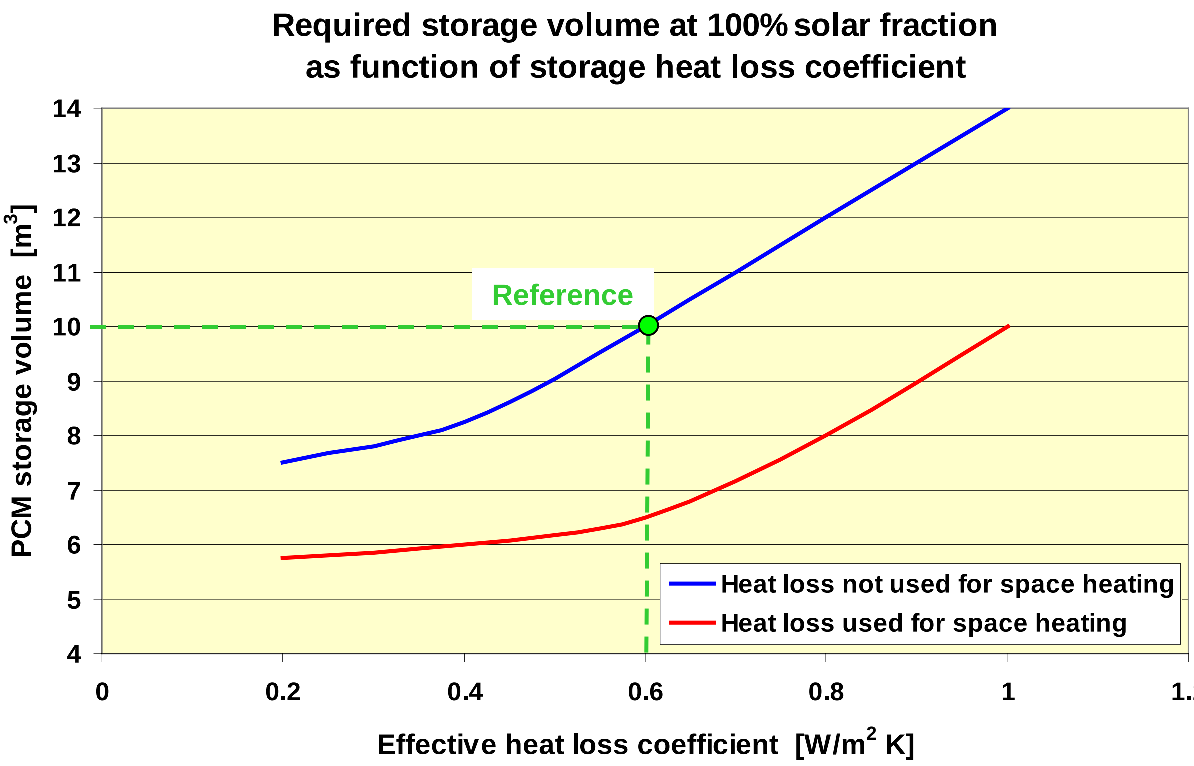



**Figure 4.** Required PCM storage volume for 100% solar fraction as function of effective storage heat loss coefficient. The blue curve shows the result if the storage heat loss is treated as pure waste. The red curve shows the result if the storage heat loss can be used for space heating in periods with space heating demand.

### Differences from Base Case (BC)
Except for the parameters that are varied the model confirms with the base case.

### Description of Results
Even though the benefit of the PCM storage with active use of supercooling is due to a considerably lower heat loss than for traditional water storage solutions the effective heat loss coefficient has a significant influence on the PCM storage performance. In case the storage heat loss cannot be used, a reduction of the effective heat loss coefficient from 0.6 W/m$^2$K to 0.4 W/m$^2$K leads to a reduction in the required total PCM storage volume from 10 m$^3$ to approximately 8 m$^3$.
In case the storage heat loss can be made usable for covering parts of the space heating demand when present the required PCM storage volume can be further reduced to approximately 6 m$^3$. In this case the influence of the effective heat loss coefficient becomes less important in the range 0.2 – 0.6 W/m$^2$K.

### Comments
None

| Sensitivity parameter: | PCM volume vs. water storage volume [$m^3$] (fixed collector area: 36 $m^2$) | 1 - 20 $m^3$ |
|---|---|---|

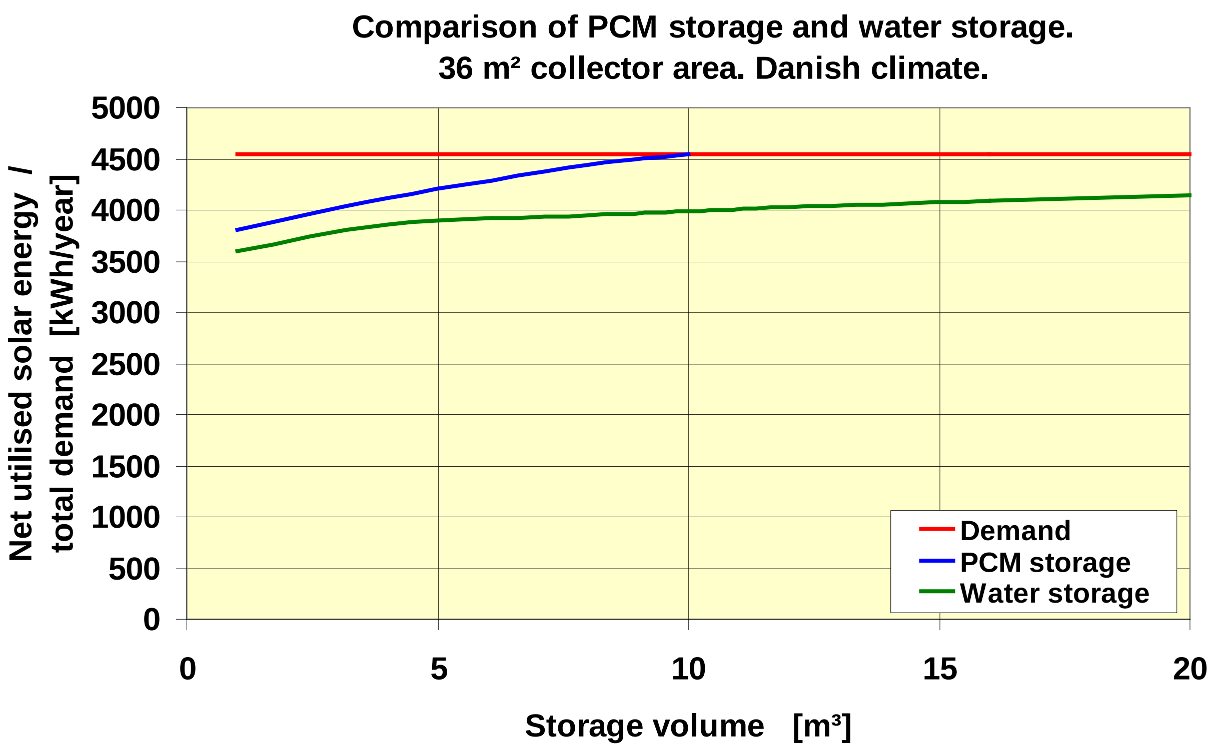



**Figure 5.** Net utilised solar energy as function of storage volume for a PCM-storage with active use of supercooling and a water storage. The red horizontal line indicates the total energy demand for both domestic hot water and space heating.

**Differences from Base Case (BC)**
The sub-section volume is 0.1 $m^3$ independent of the total storage volume.

**Description of Results**
The results show the benefit of the PCM-storage with active use of super cooling compared to a traditional water storage for which it only will be impossible to reach 100% solar fraction even with a very large volume. The difference between the PCM storage and the water storage is due to the difference in heat loss.

**Comments**
The PCM-storage and the water storage are simulated with the same model and the same insulation level. Using the same model eliminates differences due to model differences. The sub-sectioning in the model combined with the control strategy of charging one section at the time corresponds to an almost ideal stratification when simulating the water storage.

### 4.2 Definition of the optimized system

No optimized system so far

# 5 Analysis using FSC

The solar heating system has not been analysed using the FSC-method.

# 6 Lessons learned

Solar fractions of 100% are possible for low energy buildings in Denmark for solar heating systems with a PCM heat storage utilizing stable supercooling.

# 7 References

J.M. Schultz & S. Furbo. “Investigation of heat of fusion storage for solar low energy buildings”, Proceedings ISES Solar World Congress 2005.

J.M. Schultz & S. Furbo. “Heat of fusion storage with high solar fraction for solar low energy buildings”, Proceedings EUROSUN 2006.

J.M. Schultz & S. Furbo. “Solar heating systems with heat of fusion storage with 100% solar fraction for solar low energy buildings.” Proceedings ISES Solar World Congress 2007.

# 8 Appendix 1: Description of Components specific to this System

These are components that are
a) not part of the TRNSYS standard library AND
b) not part of the types used as "standard" by Task 26.

## 8.1 Type 185 : PCM storage with supercooling

Version 1.0

Parameters: 30
Inputs: 10
Outputs: 7

Please refer to description of TYPE 185 – Phase Change Material storage with super cooling by Jørgen M. Schultz, Department of Civil Engineering, Technical University of Denmark, Kgs. Lyngby, Denmark.

Availability: DTU