# System Simulation Report
# System : HEIG-VD-W and HEIG-VD-PCM

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

## Report C6.1 of Subtask C

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# Report on System Simulation

# C6.1: Appendix 1 of report C6

# HEIG-VD-W and HEIG-VD-PCM

by

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A technical report of Subtask C

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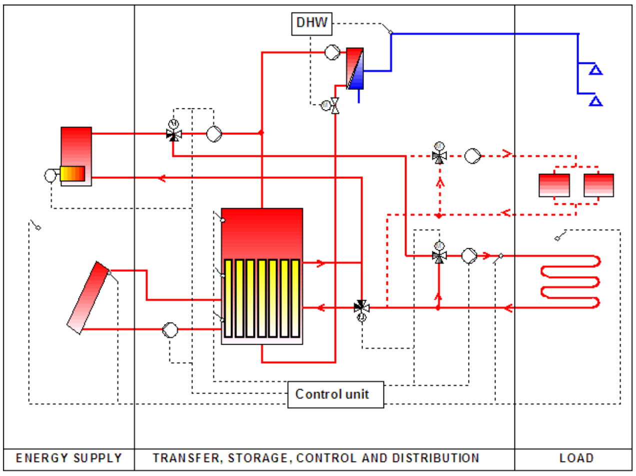
# Content

# 1 General description of HEIG-VD-W and HEIG-VD-PCM

## Main features

This system was design for a single family house to provide energy for the space heating and the domestic hot water (DHW). The water storage tank can contain phase change material (PCM – yellow part see figure here under), but not in the upper part of the tank to get enough power to provide the DHW. The global ratio of PCM is about 50% in volume. The solar collector loop of this installation is a drain back system. The storage tank, space heating and solar loop use water as heat transfer fluid. DHW preparation is done with an external flat plate heat exchanger. The space heating demand is fulfilled by solar energy with an auxiliary gas boiler.

## Heat management philosophy




Solar loop:

When the collector temperature is higher than the bottom temperature of the storage tank, the solar pump is switched on. The solar loop uses a constant flow rate without stratification. The maximal temperature inside the storage tank depends on the PCM type. Some PCM don't support high temperature, therefore, if the storage tank temperature is too high (80°C for some PCM) or if the collector temperature is higher than 90°C the solar pump is switch off.

Auxiliary boiler:

The gas boiler has a modulated burner. This gas boiler provides energy for the space heating loop without going through the storage tank. There is no heat charge in the space heating part of the tank. Thus the storage heat losses are reduced and the solar tank part is bigger.

Space heating:

If the return temperature of the space heating loop is lower than the temperature in the middle of the tank, the energy is taken from the storage tank. If the temperature level in the tank is not high enough, the gas boiler switches on. The set point temperature for the space heating loop depends of the outside temperature and the room temperature.

Preparation of DHW:

The auxiliary heat for the DHW demand is provided by the gas burner, and during this step, the space heating loop is interrupted. In the upper part (DHW) of the tank, the set point temperature is 57 °C with a dead band of ±3 °K. The DHW temperature at the output of the external heat exchanger is regulated by a temperature control valve. Due to the instantaneous DHW preparation, there is no legionella risk.

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

As there is no buffer storage the space heating loop requires a modulated burner.. If a non modulated burner is used, there is too many start-up cycling. On the other hand, the space heating demand influences only the nominal power of the boiler.

## Cost (range) and Market distribution

This kind of installation is not a commercialised combisystem. So it is difficult to give its total cost.

# 2 Modelling of the system

## 2.1 TRNSYS model

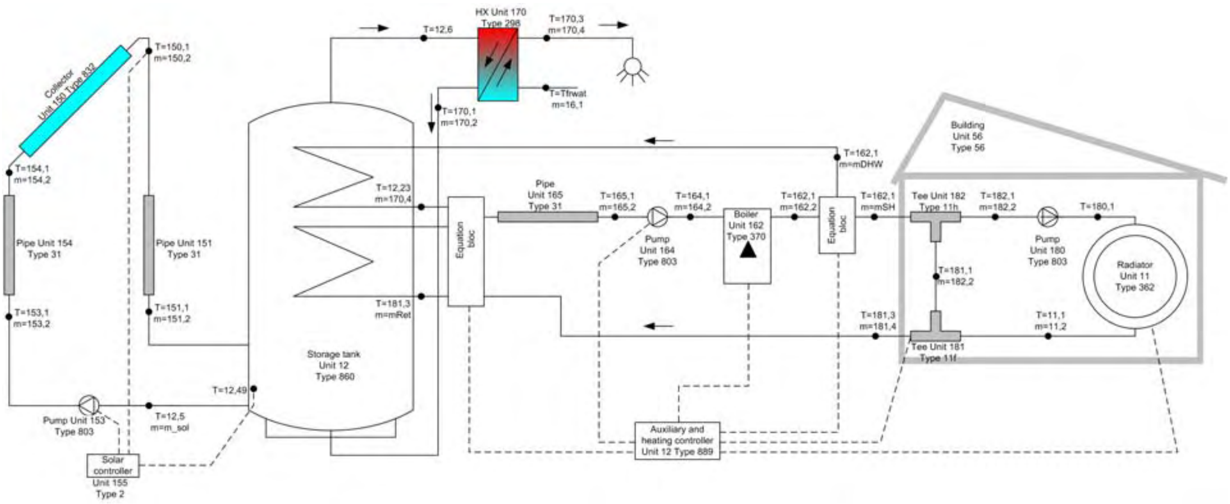



**Figure 1.** TRNSYS model of the HEIG-VD system, with or without PCM

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

The simulated system has no internal heat exchanger. Figure 1 shows the storage tank with two internal heat exchangers. In fact the type860 (type60+PCM) has only two double ports. To simulate other double ports, we introduce a heat exchanger with a large heat exchange area and a high conductivity coefficient (555 [W/m.K] or 2000 [kJ/hr.m.K]).

### 2.2.1 General Setting in the TRNEDIT template

***General Settings (to be chosen by TRNEDIT):***

| | |
|---|---|
| ***Main*** | |
| simulation timestep | 1/20 hr |
| tolerance integration / convergence | 0.003 / 0.003 |
| length of simulation | 13 months |
| climate | Zürich |
| building | SFH30 |
| ***Auxiliary*** | |
| Nominal Power of Auxiliary | 34200 kJ/hr |
| Set temperature Auxiliary into store | 57 °C |
| Auxiliary temperature rise | 6 K |
| ***Collector*** | |
| type | flat plate selective (ref) |
| aperture area | 20 m$^2$ |
| tilt angle | 45° |
| azimuth (0° = south, 90° = west, 270° east) | 0° |

| | |
|---|---|
| ***Collector (continuation)*** | |
| primary loop specific mass flow rate | 15 kg/hm$^2$ |
| upper / lower dead band (switch on / off) | 7 K / 3 K |
| relative height of low temperature sensor in store | 0.083 |
| cut-off temperature of collector | 80 °C |
| boiling temperature of collector fluid | 90 °C |
| ***Store*** | |
| storage volume | 0.83 m$^3$ |
| insulation thickness ($\lambda$=0.042 W/mK) | 0.15 m |
| correction factor for heat loss | No correction factor |

### 2.2.2 Collector

| Type: 832 | Version Number: 2.06 | |
|---|---|---|
| Collector | $\eta_0$ | 0.8 - |
| | $a_1$ | 3.5 W/m²-K |
| | $a_2$ | 0.015 W/m²-K² |
| | inc. angle modifier (50°) | 0.9 - |
| | Area | 20 m² |
| | Specific mass flow | 15 l/m²h |

### 2.2.3 Heat exchanger of collector loop

No heat exchanger

### 2.2.4 Pipes between Collector and Storage:

| | | |
|---|---|---|
| Model: | One Type 31 for hot side and one Type 31 for cold side | |
| Pipes: | Inner diameter: 0.014 m | Total Length: 30 m |
| **INSULATION:** | **THICKNESS 20 MM (4.275 W/M²-K)** | **THERMAL CONDUCTIVITY: 0.042 W/M-K** |

### 2.2.5 Control of the collector loop

Type 2

| ***Reason*** | ***Sensor*** | ***Off-Criteria*** | ***Hyst.*** |
|---|---|---|---|
| Upper dead band (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 | |
| Collector stagnation | Collector Temperature | Boiling Temp. of fluid as defined by user (TRNEDIT) | 10 K |
| Storage tank protection | Temperature in the uppermost Node of the store | Cut-off Temperature T_in as defined by user (TRNEDIT) | 2 K |

### 2.2.6 Storage:

Type: 860 (Specific type)

| | | |
|---|---|---|
| Storage tank | Total volume | 0.83 m³ |
| | Height | 1.8 m |
| | Store volume for auxiliary | 0.0 m³ |
| | Number of nodes | 18 |
| | Media: | Water |
| | Insulation thickness, thermal conductivity | 15 cm, 0.042 W/m-K |
| | Start $\Delta\vartheta$, hysteresis, Collector loop | 7 K, 3 K |

**Relative heights of store doubleports, heat exchangers and temperature sensors**

| ***Doubleport description*** | ***relative height*** | ***Dp Nr.*** |
|---|---|---|
| inlet of collector loop | 0.333 | 1 |
| outlet of collector loop | 0.0 | 1 |
| inlet of DHW loop | 0.0 | 2 |
| outlet of DHW loop | 1 | 2 |

| ***Heat exchanger description*** | ***relative height*** | ***Hx Nr.*** |
|---|---|---|
| inlet of auxiliary for DHW | 1 | 1 |
| outlet of auxiliary for DHW | 0.778 | 1 |
| inlet of Space Heating loop | 0.555 | 2 |
| outlet of Space Heating loop | 0.333 | 2 |

| ***Sensor description*** | ***relative height*** |
|---|---|
| Collector control temperature | user defined (TRNEDIT) |
| Storage protection temperature | 0.75 |
| Auxiliary On/Off temperature | 0.861 |

### 2.2.7 Auxiliary boiler:

Type 370 – Specific Type, data defined by Heimrath, Haller 2007

| ***Nr.*** | ***Description*** | ***Value(s)*** |
|---|---|---|
| 1 | temperature set point for auxiliary DHW to store | $T_{aux,set}$ [°C] set by the user (TRNEDIT) |
| 2 | Fuel type | 2 (natural gas high) |
| 3 | ambient temperature at location of boiler | 15 [°C] |
| 4 | standby temperature | 35 [°C] |
| 5 | hysteresis for standby temperature | 5 [K] |
| 6 | maximum water temperature | 90 [°C] |
| 7 | nominal power | set by the user (TRNEDIT) |
| 8 | air surplus (lambda) value | 1.2 |
| 9 | lowest modulation factor | 0.12 (ELCO THISION) |
| 10 | mass of the boiler water | 3.2 [kg] |
| 11 | temperature difference between flue gas and return temperature of water | 10 [K] |
| 12 | radiation losses | 3.5 [%] |
| 13 | standby losses as percent of nominal power | 0 [%] |
| 14 | simulation mode | 0 (original) |
| 15 | number of nodes in heat exchanger | 10 |
| 16 | exhaust gas temperature at entrance of heat exchanger | 1000 |
| 17 | minimum flow on water side | =MIN(800,Mdot80+200) |

Type 889 – Specific type is used as auxiliary controller.

| ***Description*** | ***Value(s)*** |
|---|---|
| room set temperature | 19.5 [°C] |
| ambient design temperature | taken from dataset for location chosen by the user |
| set temperature for auxiliary heat supplied to store for DHW preparation with dead band | 54 ±3 [°C] |
| nominal mass flow rate for DHW preparation | = MIN(800,Mdot80+200) |

### 2.2.8 Building

Type56 – One Zone Model, (Geometric Data defined in defined by Heimrath, Haller 2007)

### 2.2.9 Heat distribution

Radiators Type 362

| *Nr.* | *Description* | *Value(s)* |
|---|---|---|
| 1-5 | length of supply pipe and exhaust pipe respectively | not used |
| 6 | specific heat of fluid | $Cp_{Wat}$ =4.19 [kJ/kg.K] |
| 7 | mass flow rate of fluid | Mdot80 |
| 8 | radiative fraction of total emitted power | 0.35 |
| 9 | nominal power of radiator | $Q_{Rd,n}$ |
| 10 | radiator exponent | $n_{Rd}$ = 1.3 |
| 11 | thermal capacitance of radiator | 1150 [kJ/K] |
| 12 | initial temperature | 55 [°C] |

(Data defined in defined by Heimrath, Haller 2007)

The mass flow in the radiators is constant.

### 2.2.10 Draw-Off loop

Type 805. The overall heat transfer coefficient of the heat exchanger has been set to a value which results in a return temperature of 15 °C to the store in the case of 10 °C cold water temperature, 60 °C temperature from store and a secondary mass flow rate (DHW) of 1200 kg/h.

| *Nr.* | *Description* | *Value(s)* |
|---|---|---|
| 1,2 | specific heat capacity of primary and secondary side fluid respectively | CpWat |
| 3 | maximum allowed flow rate on primary (hot) side | 1400 [kg/h] |
| 4 | temperature set point for secondary side outlet | 45 [°C] |
| 5 | overall heat transfer coefficient UA of heat exchanger | 19200 [kJ/hr.K] |

## 2.3 Validation of the system model

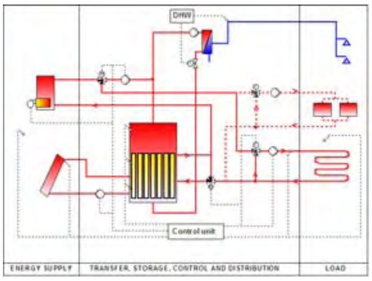
There is no measurement to validate the simulated system. The solar, DHW and heating loops keep the reference template configuration. The auxiliary, the storage tank and the controller are new systems.

# 3 Simulations for testing the library and the accuracy

The used simulation time step is 1/20 (or 1/30) h and the tolerances for convergence and integration are 0.003.

# 4 Sensitivity Analysis and Optimization

## 4.1 Presentation of results




PCM and water storage tank with decentralised auxiliary boiler (SCS-Switzerland)

| Main parameters (optimised Base Case (BC)): | | | |
|---|---|---|---|
| Building: | *SFH 30* | Storage Volume: | *0.83 m³* |
| Climate: | *Zurich* | Storage height | *1.8 m* |
| Collectors area: | *15 m²* | **POSITION OF AUXILIARY IN/OUTLET: DHW:** | *1/0.778* |
| Collector type: | *Standard Flat Plate* | Relative position of in/outlets:<br>DHW:<br>Solar : | <br>*0/1*<br>*0.333/0* |
| Specific flow rate (Collector) | *15 kg/m²-h* | **POSITION OF SPACE HEATING IN/OUTLET:** | *0.555/0.333* |
| Collector azimuth/tilt angle | *0 / 45°* | Thermal insulation | *15 cm* |
| Collector upper/lower dead band | *7 / 3 °K* | Nominal auxiliary heating rate | *9.5 kW* |
| Storage medium | *Water* | DHW set point temperature (in storage tank) / dead band | *54 °C / ± 3°* |
| Simulation parameter: | | Storage nodes | *46.1 l/Node*<br>*18 nodes* |
| Time step | *1/20 h* | Tolerances<br>Integration Convergence | *0.003 /*<br>*0.003* |

| Summary of Sensitivity Parameters | | | |
|---|---|---|---|
| Parameter | Variation | [1]Variation in $f_{sav,ext}$ | |
| Base Case (BC) | - | 54.02% | |
| Collector size [$m^2$] (fixed store size (0.83 $m^3$) | 10-25 | 48.48 – 59.53% | Figure 2 |
| Storage medium | Water/Water+RT27 /Water+RT35 /Water+RT42 | 54.02 – 55.13% | Figure 3 |
| Store Size [$m^3$] (fixed collector area of 15 $m^2$) | 0.83 – 2.50 | 54.68 – 53.38% | Figure 4 |
| Collector Azimuth [°] (fixed tilt of 45°) | -90 - 90 | 43.37 – 54.02% | Figure 5 |
| Collector Tilt [°] (fixed azimuth of 0°) | 15 – 90 | 49.05 – 54.53% | Figure 6 |
| Specific Collector flow rate [kg/$m^2$-h] | 15 - 45 | 53.44 - 54.02% | Figure 7 |
| Collector Controller $dT_{stop}$ [K] | 1 - 5 | 53.93 – 54.18% | Figure 8 |
| Collector Controller $dT_{start}$ [K] | 5– 12 | 53.79 – 54.02% | Figure 9 |
| Climate (30 kWh MFH – Base Case (BC)) | Bar./Mad. / Zur. / Stock. | 96.3% / 89.6% / 54.0%/ 44.7% | Figure 10 |
| DHW Heat Exch. UA [%] (variation from BC value - 5'330 W/K) | -50 - +100 | 52.89 – 54.27% | Figure 11 |
| DHW thermostat temperature [°C] | 50 - 60 | 53.05 – 54.38% | Figure 12 |
| DHW dead band [K] | ±2 - ±5 | 53.98 – 54.08% | Figure 13 |

**[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 [$m^2$]<br>(fixed store size 0.83 $m^3$) | 10 - 25 $m^2$ |
|---|---|---|

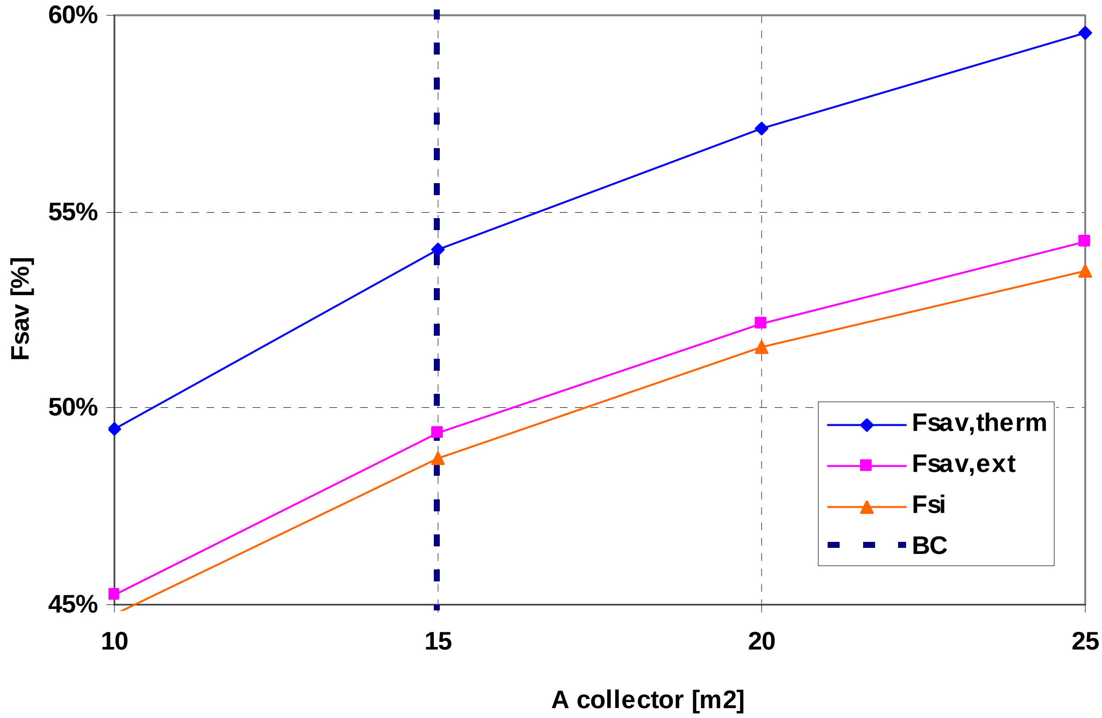



*Figure 2. Variation of fractional energy savings vs collector size for a fixed storage volume of 0.83 $m^3$.*

**Differences from Base Case (BC)**
None

**Description of Results**
As expected, the increase of collector area increases the $f_{save}$. There are very few penalties occurred for the settings, so that $f_{si} \approx f_{sav,ext}$

**Comments**
With a small store volume, it is not consistent to run simulation with too high collector area.

| Sensitivity parameter: | Storage medium | Water/Water+RT27 /Water+RT35 /Water+RT42 |
|---|---|---|

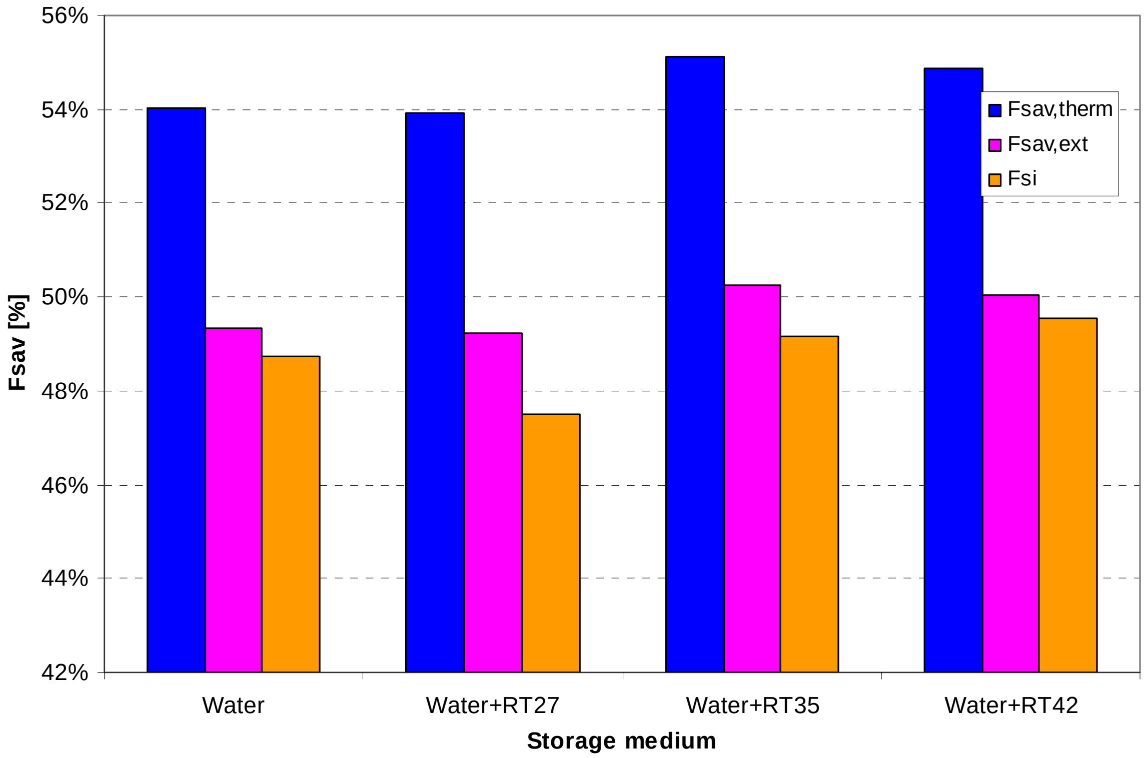



*Figure 3. Variation of fractional energy savings for different heat storage compositions.*

**Differences from Base Case (BC)**
Bulk elements of phase change materials are plunge in the water tank. The container diameter is 50mm. There is no PCM in the upper part of the tank to avoid DHW penalty. In fact the heat exchange between water and PCM module is not high enough to provide power for DHW draw-off

**Description of Results**
With PCM, the performance improvement is very low, compare to the storage tank with only water. There is an optimum due to the correlation between the phase change temperature and the space heating temperature.

**Comments**
It seems difficult to use this kind of PCM with a solar combisystem to get a big improvement. As well, the extra cost is a limitation with this material for this low gain.

| Sensitivity parameter: | Store size [$m^3$] (fixed collector area of 15 $m^2$) | 0.83 – 2.5 $m^3$ |
|---|---|---|

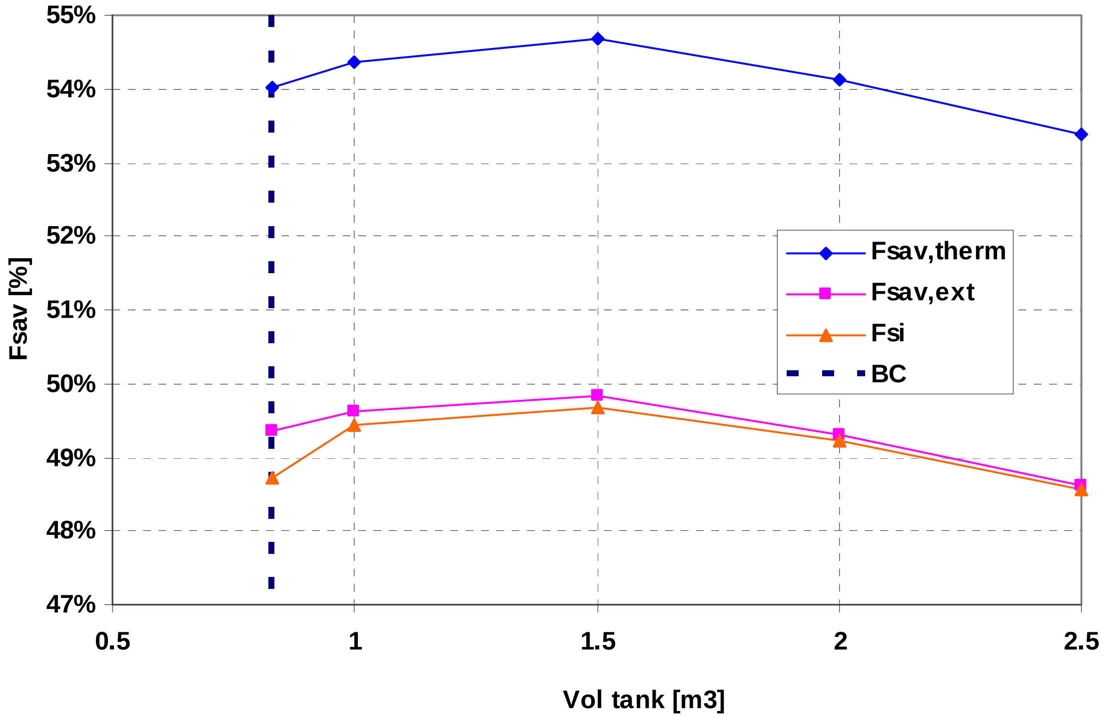



*Figure 4. Variation of fractional energy savings vs storage tank volume for a fixed collector area of 15 $m^2$.*

### Differences from Base Case (BC)

- The DHW volume heated by the auxiliary change proportionally with the volume of the tank.
- The sensors for the thermostats controlling the store charging were always on the same height, at the outlet of heater.
- The height of the store is always the same (1.8 m).
- The insulation is the same for the different volume.

### Description of Results

The optimum is around 1.5 [$m^3$]in Zürich, with 15 [$m^2$] of collectors and the 30 [kWh.$m^2$.a] building. The base case seems the limit before increase the DHW penalty.

### Comments

Even the base case is not the optimum; this storage volume allows going through standard door in single family house.

| Sensitivity parameter: | Collector azimuth [°]<br>(fixed tilt of 45°) | -90 – 90° |
|---|---|---|

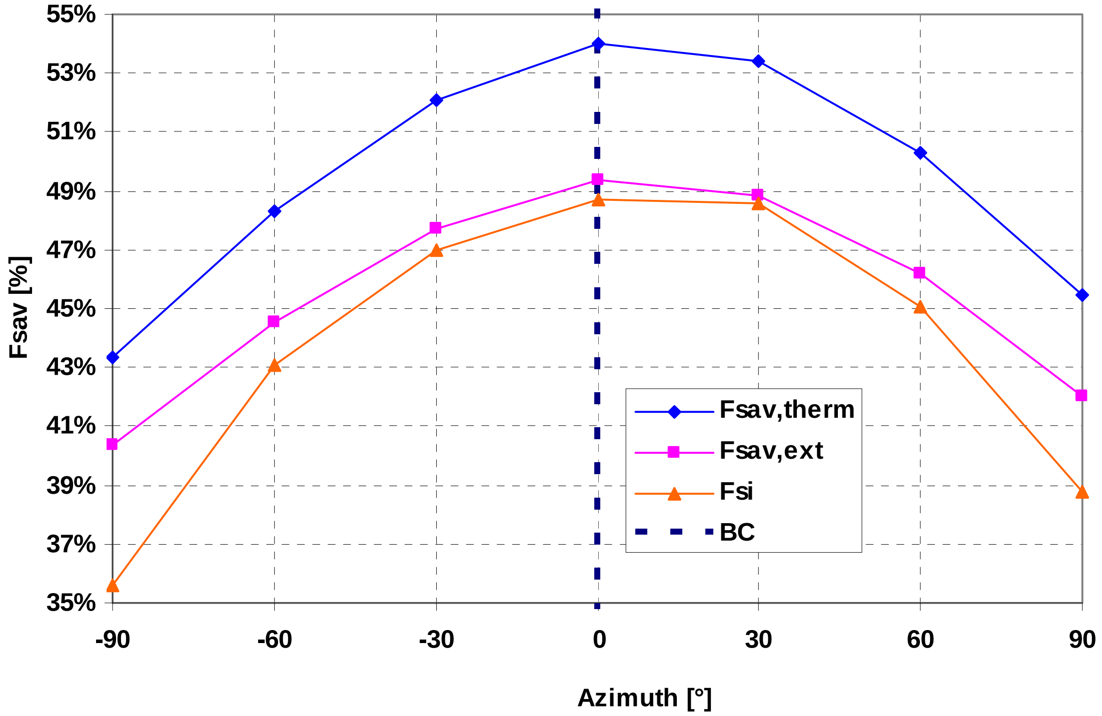



*Figure 5. Variation of fractional energy savings vs collector azimuth for a fixed tilt angle of 45°.*

**Differences from Base Case (BC)**
None

**Description of Results**
Here $F_{sav}$ shows an optimum with a small shift in the west.

**Comments**
The value for –90° and +90° are extreme.

| Sensitivity parameter: | Collector tilt [°] (fixed azimuth of 0°) | 15 – 90° |
|---|---|---|

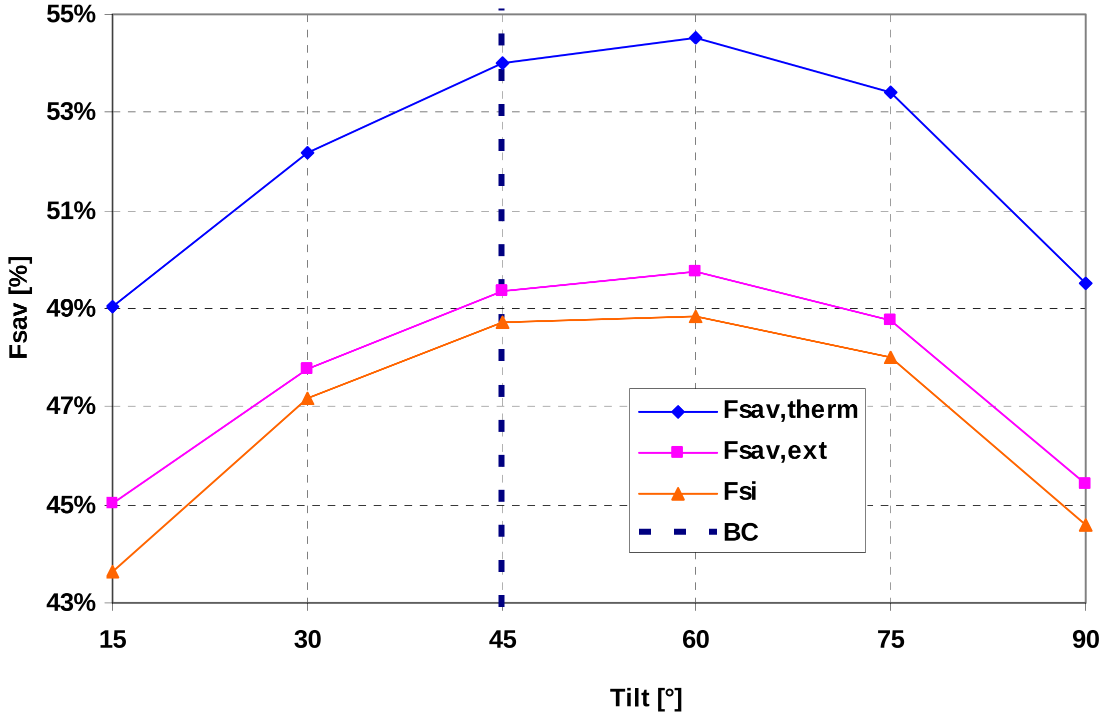



*Figure 6. Variation of fractional energy savings vs collector tilt, for afixed azimuth angle of 0°.*

**Differences from Base Case (BC)**
None

**Description of Results**
In this case, the $F_{sav}$ shows an optimum around 60° tilt. During winter time the sun height is low and we need to tilt the collector plan more than 45°.

**Comments**
The common tilt angle of roof is between 30 to 45°. It is possible to put solar collector on a wall or a bank to get an optimum angle.

| Sensitivity parameter: | Specific Collector flow rate [kg/m²-h] | 15 – 45 |
|---|---|---|

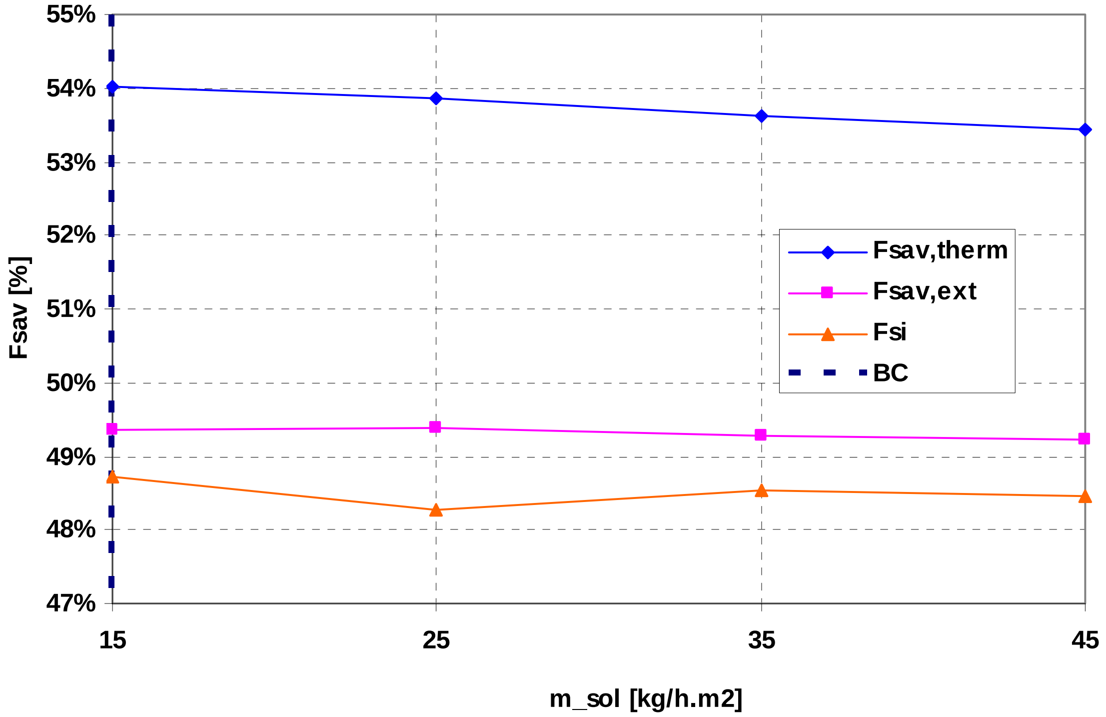



*Figure 7. Variation of fractional energy savings vs specific collector flow rate.*

**Differences from Base Case (BC)**
None

**Description of Results**
The store charge flow affects slightly the annual savings.

**Comments**
None

| Sensitivity parameter: | Collector Controller $dT_{stop}$ [K] | 1 – 5 |
|---|---|---|

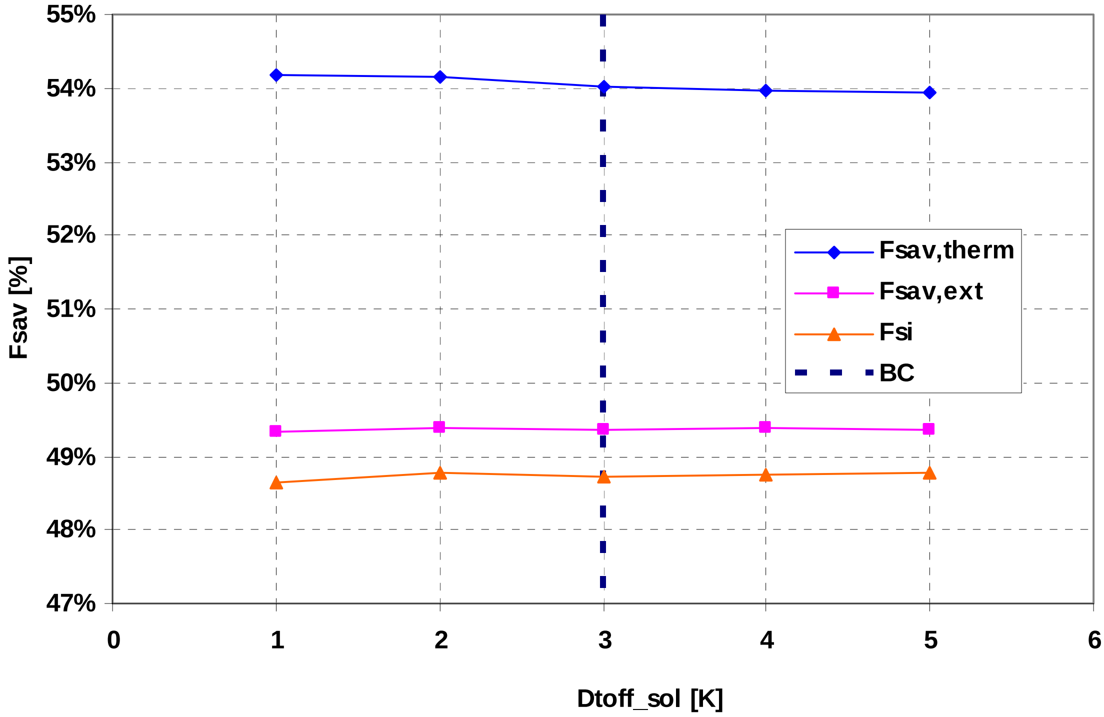



*Figure 8. Variation of fractional energy savings vs collector controller $dT_{stop}$.*

**Differences from Base Case (BC)**
$Dt_{start}$ unchanged.

**Description of Results**
The $dT_{stop}$ affects slightly the annual savings.

**Comments**
None

| **Sensitivity parameter:** | Collector Controller $dT_{start}$ [K] | 5 – 12 |
|---|---|---|

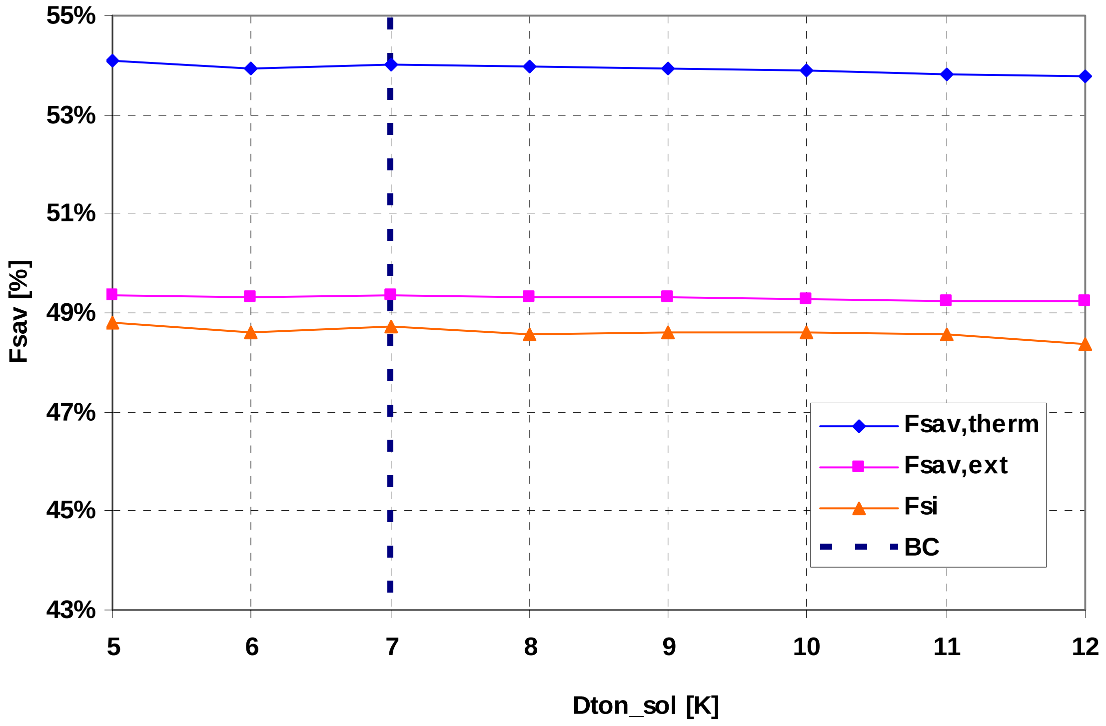



*Figure 9. Variation of fractional energy savings vs collector controller $dT_{start}$.*

**Differences from Base Case (BC)**
$Dt_{stop}$ unchanged.

**Description of Results**
As for $dT_{stop}$ , the $dT_{start}$ affects the annual savings slightly.

**Comments**
None

| **Sensitivity parameter:** | Climate<br>(30 kWh MFH – Base Case (BC)) | Bar./Mad. / Zur. / Stock. |
|---|---|---|

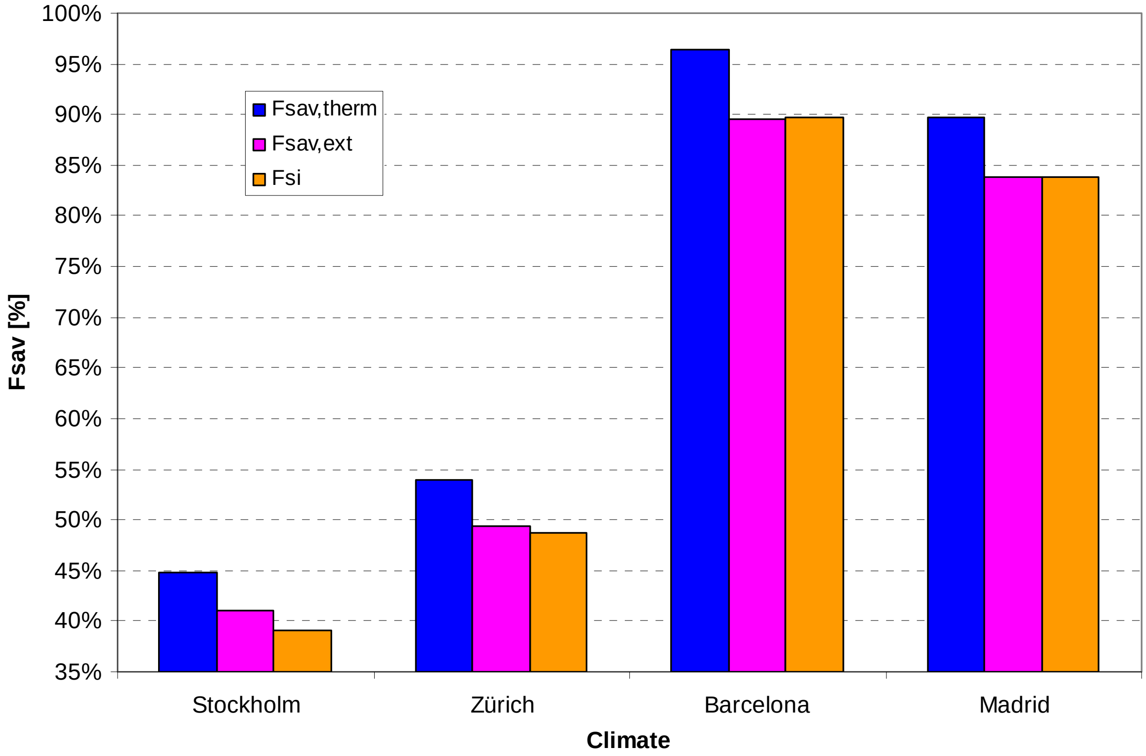



*Figure 10. Variation of fractional energy savings for different climates.*

**Differences from Base Case (BC)**
None

**Description of Results**
None

**Comments**
It seems that there are two kind of climate. There is not lot of difference between Stockholm and Zürich or Barcelona and Madrid.

| **Sensitivity parameter:** | DHW Heat Exch. UA [%]<br>(variation from BC value - 5'330 W/K) | -50 - +100 |
|---|---|---|

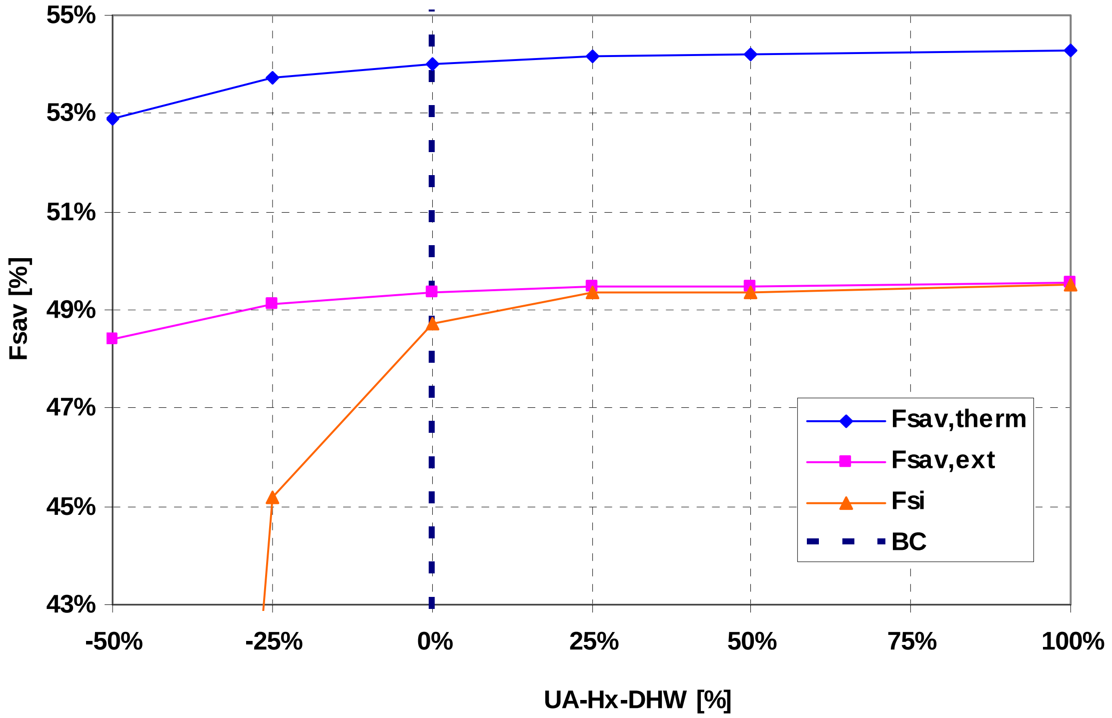



*Figure 11. Variation of fractional energy savings vs UA value of the DHW heat exchanger.*

**Differences from Base Case (BC)**
None

**Description of Results**
Just under the base case, the DHW penalty is very high.

**Comments**
The UA value is nearly optimised in the base case.

| **Sensitivity parameter:** | DHW thermostat temperature [°C] | 50 - 60 |
|---|---|---|

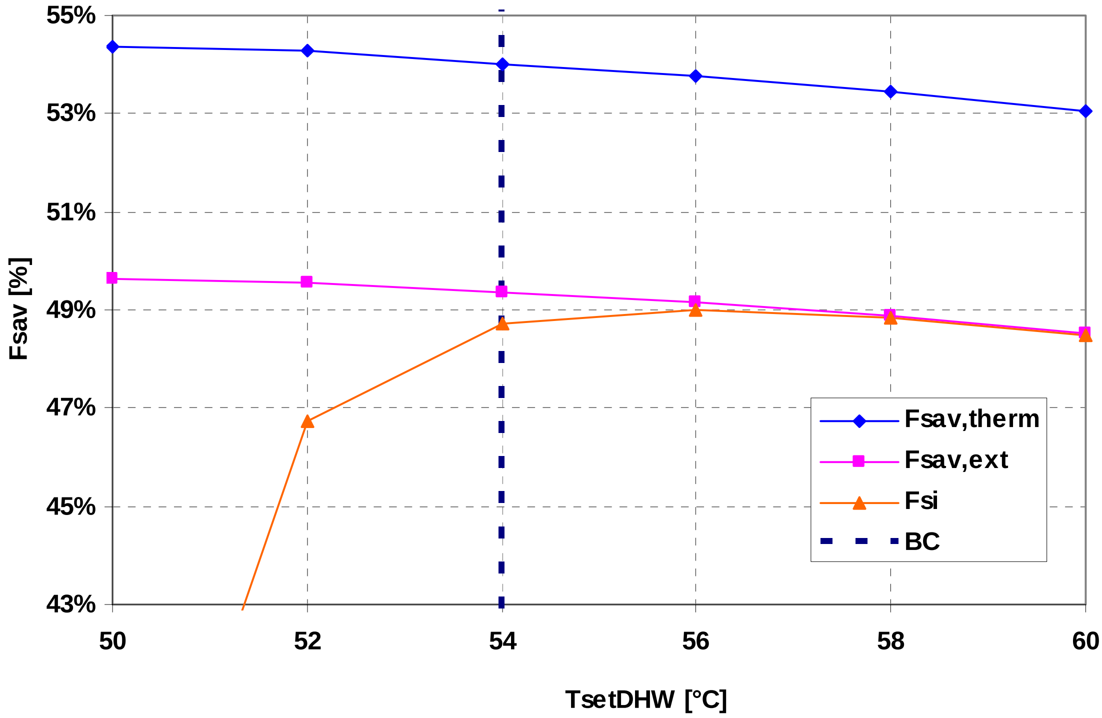



*Figure 12. Variation of fractional energy savings vs DHW thermostat temperature.*

**Differences from Base Case (BC)**
None

**Description of Results**
Just under the base case value, the DHW penalty is very high.

**Comments**
The thermostat temperature value is optimised in the base case. If we increase the thermostat temperature, the $F_{si}$ goes up but the $F_{sav}$ decreases.

| **Sensitivity parameter:** | DHW dead band [K] | ±2 - ±5 |
|---|---|---|

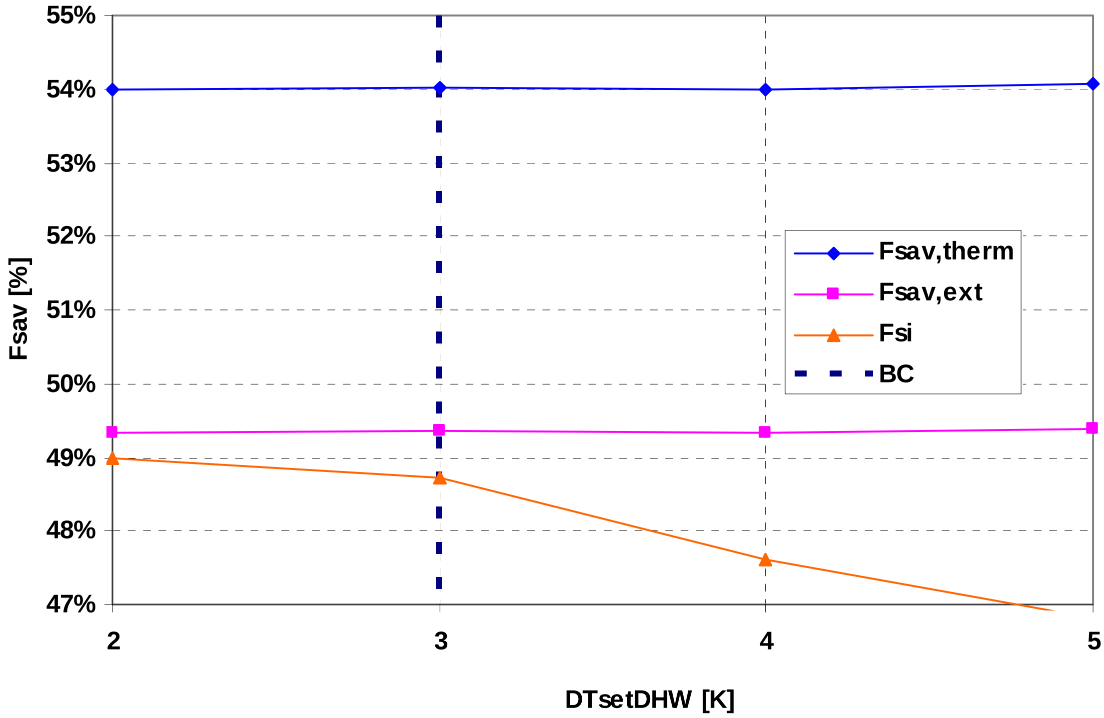



*Figure 13. Variation of fractional energy savings vs DHW dead band of the thermostat temperature.*

**Differences from Base Case (BC)**
None

**Description of Results**
Above the base case value, the DHW penalty increase.

**Comments**
To increase the $F_{sav}$, it is possible to decrease the dead band value. But its increase the number of start-up burner.

## 4.2 Definition of the optimized system

In an earlier phase of the project, experimental test have been undertaken with a solar combisystem in which aluminium containers filled with PCM where placed in the storage tank (see C3 report). The results showed a slight improvement of the performance for the storage tank with PCM. These experimental tests confirmed simulations results. This system had two internal heat exchangers and a combustion chamber which took lot place. Therefore, the PCM storage tank could be filled with only 12% in volume of PCM. Furthermore, with the integrated burner, i the PCM in the upper part of the storage tank is directly heated.

In order to increase the PCM volume, a water tank with no internal components is used. In addition, the external gas boiler doesn't heat the heating part of the tank to keep more heat capacity to the solar gain.

It is also possible to increase the storage volume (Figure 4). But in this case, it should be kept in mind that the tank's dimensions do not fit a common door.

The remaining of this chapter presents the results for this new solar combisystem with and without PCM.

# 5 Analysis using FSC'

For the optimised system the analysis based on FSC should be carried out for each building. Table 1 to 4 gives the results for the 30 kWh/m$^2$.a building. The same simulations have also been undertaken for the four other building types.

*Table 1 Results of solar system HEIG-VD-W and HEIG-VD-PCM simulations for the climate Zurich*

| Building | | SFH 30 | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Climate | | Zurich | | | | | | | |
| $V_{Store}$ | [m³] | 0.83 | | | | | | | |
| Heat storage medium | | Water | | | | Water + paraffin RT35 | | | |
| $A_{col}$ | [m²] | 10 | 15 | 20 | 25 | 10 | 15 | 20 | 25 |
| $Q_{solar,usable,heat}$ | [kWh/a] | 5476 | 6496 | 7456 | 8127 | 5476 | 6496 | 7456 | 8127 |
| $E_{aux}$ | [kWh/a] | 4661 | 4243 | 3956 | 3734 | 4582 | 4140 | 3840 | 3615 |
| $E_{ref}$ | [kWh/a] | 9227 | 9227 | 9227 | 9227 | 9227 | 9227 | 9227 | 9227 |
| $E_{total}$ | [kWh/a] | 5829 | 5390 | 5094 | 4869 | 5755 | 5294 | 4983 | 4752 |
| $E_{total,ref}$ | [kWh/a] | 10643 | 10643 | 10643 | 10643 | 10643 | 10643 | 10643 | 10643 |
| $Q_{in,store}$ | [kWh/a] | 4581 | 4850 | 5039 | 5181 | 4644 | 4979 | 5207 | 5367 |
| $Q_{out,store}$ | [kWh/a] | 3537 | 3718 | 3852 | 3959 | 3593 | 3826 | 3994 | 4112 |
| $Q_{st,aux}$ | [kWh/a] | 4717 | 4301 | 4016 | 3796 | 4625 | 4184 | 3875 | 3655 |
| $Q_{st,coll}$ | [kWh/a] | 3340 | 3822 | 4140 | 4379 | 3428 | 3951 | 4310 | 4563 |
| $Q_{st,dhw}$ | [kWh/a] | 3047 | 3047 | 3047 | 3047 | 3047 | 3047 | 3047 | 3047 |
| $Q_{st,sh}$ | [kWh/a] | 4071 | 4069 | 4066 | 4064 | 4070 | 4065 | 4065 | 4061 |
| $Q_{Coll}$ | [kWh/a] | 3646 | 4148 | 4486 | 4744 | 3725 | 4272 | 4649 | 4920 |
| $W_{pump,sol}$ | [kWh/a] | 68 | 61 | 57 | 55 | 69 | 62 | 59 | 57 |
| $W_{burn}$ | [kWh/a] | 126 | 123 | 120 | 118 | 125 | 121 | 118 | 116 |
| $W_{contr}$ | [kWh/a] | 18 | 18 | 18 | 18 | 18 | 18 | 18 | 18 |
| $W_{pump,SH}$ | [kWh/a] | 247 | 250 | 253 | 255 | 249 | 253 | 255 | 256 |
| $W_{pump,DHW}$ | [kWh/a] | 8 | 8 | 8 | 8 | 8 | 8 | 8 | 8 |
| $W_{total}$ | [kWh/a] | 467 | 459 | 455 | 454 | 469 | 461 | 457 | 455 |
| FSC | | 0.5935 | 0.7040 | 0.8081 | 0.8808 | 0.5935 | 0.7040 | 0.8081 | 0.8808 |
| FSC' | | 0.6205 | 0.7516 | 0.8765 | 0.9711 | 0.6205 | 0.7516 | 0.8765 | 0.9711 |
| $f_{sav,therm}$ | | 0.4948 | 0.5402 | 0.5713 | 0.5953 | 0.5034 | 0.5513 | 0.5838 | 0.6083 |
| $f_{sav,ext}$ | | 0.4523 | 0.4935 | 0.5214 | 0.5425 | 0.4592 | 0.5026 | 0.5318 | 0.5535 |
| $f_{si}$ | | 0.4476 | 0.4872 | 0.5154 | 0.5347 | 0.4521 | 0.4916 | 0.5218 | 0.5446 |

*Table 2 Results of solar system HEIG-VD-W and HEIG-VD-PCM simulations for the climate Stockholm*

| Building<br>Climate | SFH 30<br>Stockholm | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| $V_{Store}$ [m³] | 0.83 | | | | | | | |
| Heat storage medium | Water | | | | Water + paraffin RT35 | | | |
| $A_{col}$ [m²] | 10 | 15 | 20 | 25 | 10 | 15 | 20 | 25 |
| $Q_{solar,usable,heat}$ [kWh/a] | 5563 | 6737 | 7454 | 8170 | 5563 | 6737 | 7454 | 8170 |
| $E_{aux}$ [kWh/a] | 7092 | 6678 | 6386 | 6184 | 6999 | 6568 | 6270 | 6056 |
| $E_{ref}$ [kWh/a] | 12086 | 12086 | 12086 | 12086 | 12086 | 12086 | 12086 | 12086 |
| $E_{total}$ [kWh/a] | 8453 | 8023 | 7729 | 7519 | 8368 | 7918 | 7608 | 7397 |
| $E_{total,ref}$ [kWh/a] | 13614 | 13614 | 13614 | 13614 | 13614 | 13614 | 13614 | 13614 |
| $Q_{in,store}$ [kWh/a] | 4681 | 4966 | 5175 | 5309 | 4755 | 5086 | 5302 | 5464 |
| $Q_{out,store}$ [kWh/a] | 3673 | 3880 | 4043 | 4145 | 3751 | 3996 | 4156 | 4285 |
| $Q_{st,aux}$ [kWh/a] | 7251 | 6832 | 6539 | 6338 | 7140 | 6703 | 6405 | 6191 |
| $Q_{st,coll}$ [kWh/a] | 3249 | 3717 | 4033 | 4251 | 3348 | 3849 | 4189 | 4424 |
| $Q_{st,dhw}$ [kWh/a] | 3127 | 3128 | 3129 | 3129 | 3127 | 3128 | 3127 | 3128 |
| $Q_{st,sh}$ [kWh/a] | 6467 | 6464 | 6465 | 6462 | 6467 | 6463 | 6459 | 6461 |
| $Q_{Coll}$ [kWh/a] | 3535 | 4022 | 4350 | 4584 | 3625 | 4146 | 4501 | 4756 |
| $W_{pump,sol}$ [kWh/a] | 64 | 58 | 54 | 52 | 66 | 59 | 56 | 54 |
| $W_{burn}$ [kWh/a] | 143 | 139 | 137 | 135 | 142 | 138 | 136 | 134 |
| $W_{contr}$ [kWh/a] | 18 | 18 | 18 | 18 | 18 | 18 | 18 | 18 |
| $W_{pump,SH}$ [kWh/a] | 312 | 316 | 321 | 321 | 314 | 317 | 318 | 323 |
| $W_{pump,DHW}$ [kWh/a] | 8 | 8 | 8 | 8 | 8 | 8 | 8 | 8 |
| $W_{total}$ [kWh/a] | 545 | 538 | 537 | 534 | 547 | 540 | 535 | 536 |
| FSC | 0.4603 | 0.5575 | 0.6167 | 0.6760 | 0.4603 | 0.5575 | 0.6167 | 0.6760 |
| FSC' | 0.4779 | 0.5880 | 0.6614 | 0.7348 | 0.4779 | 0.5880 | 0.6614 | 0.7348 |
| $f_{sav,therm}$ | 0.4132 | 0.4475 | 0.4716 | 0.4884 | 0.4209 | 0.4566 | 0.4812 | 0.4989 |
| $f_{sav,ext}$ | 0.3791 | 0.4107 | 0.4323 | 0.4477 | 0.3854 | 0.4184 | 0.4411 | 0.4567 |
| $f_{si}$ | 0.2999 | 0.3905 | 0.4204 | 0.4332 | 0.3123 | 0.3674 | 0.3824 | 0.4235 |

*Table 3 Results of solar system HEIG-VD-W and HEIG-VD-PCM simulations for the climate Barcelona*

| Building | SFH 30 | | | | | |
|---|---|---|---|---|---|---|
| Climate | Barcelona | | | | | |
| $V_{Store}$ [m³] | 0.83 | | | | | |
| Heat storage medium | Water | | | Water + paraffin RT35 | | |
| $A_{col}$ [m²] | 10 | 15 | 20 | 10 | 15 | 20 |
| $Q_{solar,usable,heat}$ [kWh/a] | 4353 | 4353 | 4353 | 4353 | 4353 | 4353 |
| $E_{aux}$ [kWh/a] | 319 | 159 | 123 | 337 | 178 | 122 |
| $E_{ref}$ [kWh/a] | 4353 | 4353 | 4353 | 4353 | 4353 | 4353 |
| $E_{total}$ [kWh/a] | 825 | 634 | 579 | 845 | 655 | 583 |
| $E_{total,ref}$ [kWh/a] | 6054 | 6054 | 6054 | 6054 | 6054 | 6054 |
| $Q_{in,store}$ [kWh/a] | 4313 | 4462 | 4527 | 4439 | 4588 | 4646 |
| $Q_{out,store}$ [kWh/a] | 2908 | 2930 | 2938 | 2931 | 2949 | 2957 |
| $Q_{st,aux}$ [kWh/a] | 303 | 155 | 120 | 316 | 169 | 118 |
| $Q_{st,coll}$ [kWh/a] | 4120 | 4392 | 4484 | 4209 | 4488 | 4588 |
| $Q_{st,dhw}$ [kWh/a] | 2828 | 2828 | 2828 | 2828 | 2828 | 2828 |
| $Q_{st,sh}$ [kWh/a] | 204 | 202 | 202 | 202 | 201 | 201 |
| $Q_{Coll}$ [kWh/a] | 4574 | 4859 | 4952 | 4648 | 4940 | 5043 |
| $W_{pump,sol}$ [kWh/a] | 76 | 63 | 56 | 77 | 65 | 58 |
| $W_{burn}$ [kWh/a] | 81 | 80 | 80 | 81 | 80 | 80 |
| $W_{contr}$ [kWh/a] | 18 | 18 | 18 | 18 | 18 | 18 |
| $W_{pump,SH}$ [kWh/a] | 19 | 20 | 20 | 20 | 20 | 21 |
| $W_{pump,DHW}$ [kWh/a] | 8 | 8 | 8 | 8 | 8 | 8 |
| $W_{total}$ [kWh/a] | 202 | 190 | 182 | 203 | 191 | 184 |
| FSC | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 |
| FSC' | 1.1696 | 1.2855 | 1.4014 | 1.1696 | 1.2855 | 1.4014 |
| $f_{sav,therm}$ | 0.9267 | 0.9634 | 0.9718 | 0.9226 | 0.9591 | 0.9719 |
| $f_{sav,ext}$ | 0.8638 | 0.8953 | 0.9044 | 0.8605 | 0.8918 | 0.9037 |
| $f_{si}$ | 0.8663 | 0.8978 | 0.9078 | 0.8630 | 0.8944 | 0.9071 |

*Table 4 Results of solar system HEIG-VD-W and HEIG-VD-PCM simulations for the climate Madrid*

| Building<br>Climate | SFH 30<br>Madrid | | | | | |
|---|---|---|---|---|---|---|
| $V_{Store}$ [m³] | 0.83 | | | | | |
| Heat storage medium | Water | | | Water + paraffin RT35 | | |
| $A_{col}$ [m²] | 10 | 15 | 20 | 10 | 15 | 20 |
| $Q_{solar,usable,heat}$[kWh/a] | 5190 | 5341 | 5341 | 5190 | 5341 | 5341 |
| $E_{aux}$ [kWh/a] | 788 | 554 | 440 | 775 | 537 | 419 |
| $E_{ref}$ [kWh/a] | 5341 | 5341 | 5341 | 5341 | 5341 | 5341 |
| $E_{total}$ [kWh/a] | 1426 | 1163 | 1034 | 1417 | 1150 | 1017 |
| $E_{total,ref}$ [kWh/a] | 7189 | 7189 | 7189 | 7189 | 7189 | 7189 |
| $Q_{in,store}$ [kWh/a] | 4718 | 4913 | 5010 | 4874 | 5082 | 5185 |
| $Q_{out,store}$ [kWh/a] | 3317 | 3402 | 3450 | 3380 | 3471 | 3524 |
| $Q_{st,aux}$ [kWh/a] | 783 | 555 | 442 | 760 | 530 | 412 |
| $Q_{st,coll}$ [kWh/a] | 4426 | 4748 | 4896 | 4538 | 4878 | 5041 |
| $Q_{st,dhw}$ [kWh/a] | 2978 | 2978 | 2978 | 2978 | 2978 | 2978 |
| $Q_{st,sh}$ [kWh/a] | 876 | 874 | 872 | 874 | 872 | 871 |
| $Q_{Coll}$ [kWh/a] | 4863 | 5207 | 5356 | 4958 | 5315 | 5487 |
| $W_{pump,sol}$ [kWh/a] | 77 | 65 | 59 | 78 | 66 | 61 |
| $W_{burn}$ [kWh/a] | 86 | 85 | 84 | 85 | 84 | 83 |
| $W_{contr}$ [kWh/a] | 18 | 18 | 18 | 18 | 18 | 18 |
| $W_{pump,SH}$ [kWh/a] | 66 | 68 | 69 | 68 | 69 | 70 |
| $W_{pump,DHW}$ [kWh/a] | 8 | 8 | 8 | 8 | 8 | 8 |
| $W_{total}$ [kWh/a] | 255 | 244 | 238 | 257 | 145 | 239 |
| FSC | 0.9717 | 1.0000 | 1.0000 | 0.9717 | 1.0000 | 1.0000 |
| FSC' | 1.1081 | 1.2294 | 1.3240 | 1.1081 | 1.2294 | 1.3240 |
| $f_{sav,therm}$ | 0.8524 | 0.8964 | 0.9176 | 0.8548 | 0.8994 | 0.9215 |
| $f_{sav,ext}$ | 0.8016 | 0.8383 | 0.8562 | 0.8029 | 0.8401 | 0.8586 |
| $f_{si}$ | 0.8030 | 0.8388 | 0.8586 | 0.7953 | 0.8327 | 0.8593 |

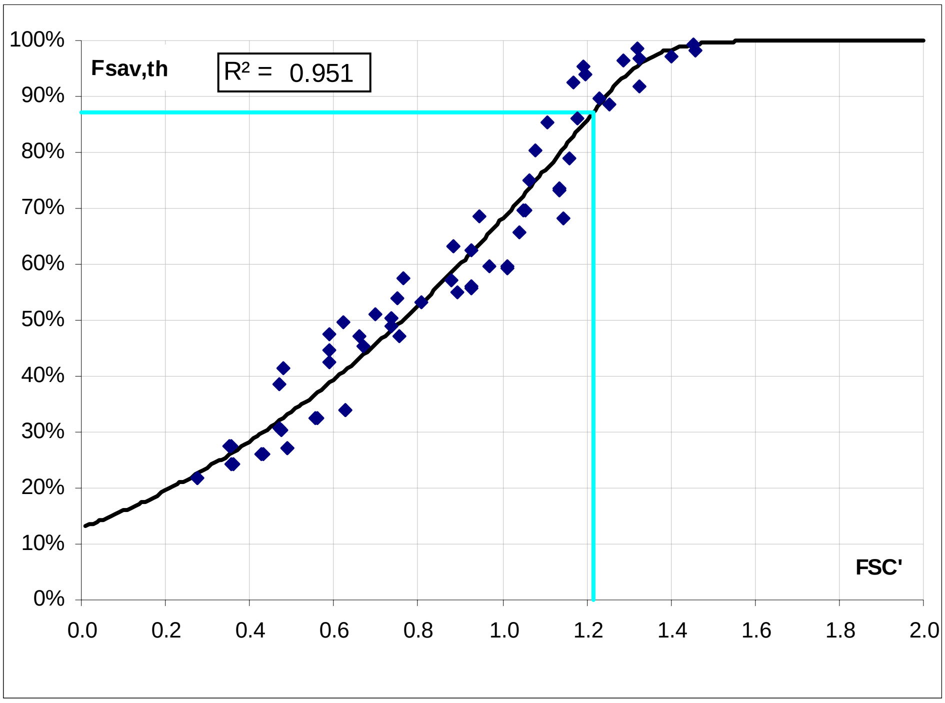



*Figure 14. Water system, variation of thermal fractional energy savings with the fractional solar consumption (FSC') for 4 climates ( Zürich, Stockholm, Barcelona and Madrid) and five loads (15, 30, 60, 100 and 100n kWh/m²a single family building).*

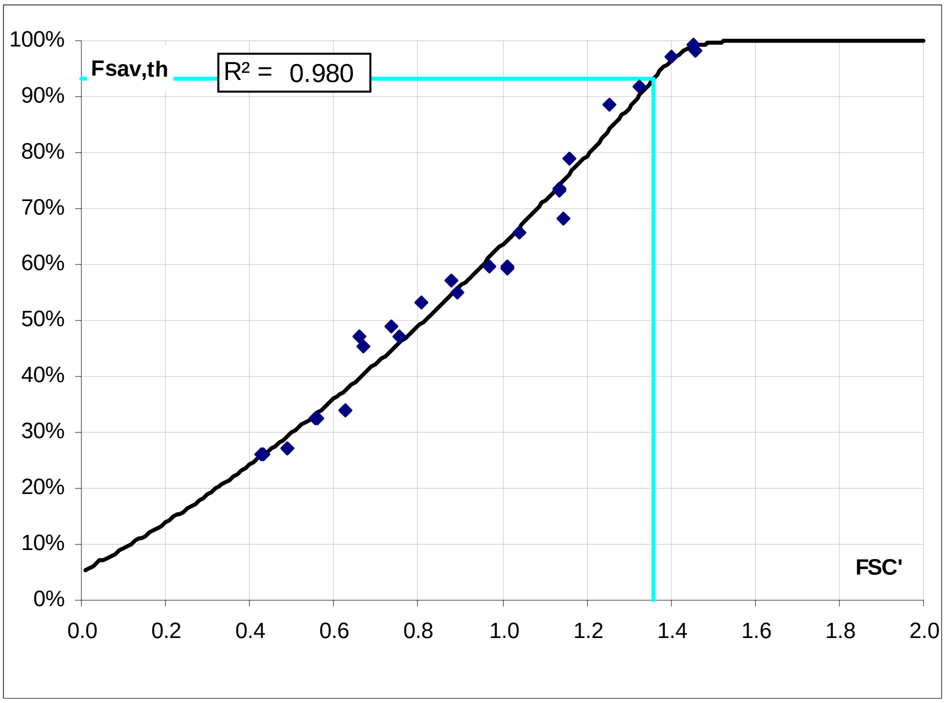



*Figure 15. Water system, variation of thermal fractional energy savings with the fractional solar consumption (FSC') for 4 climates ( Zürich, Stockholm, Barcelona and Madrid) and five loads (15, 30, 60, 100 and 100n kWh/m²a single family building) with a storage ratio of 33.2 and 45.1 l/m$^2$ collector.*

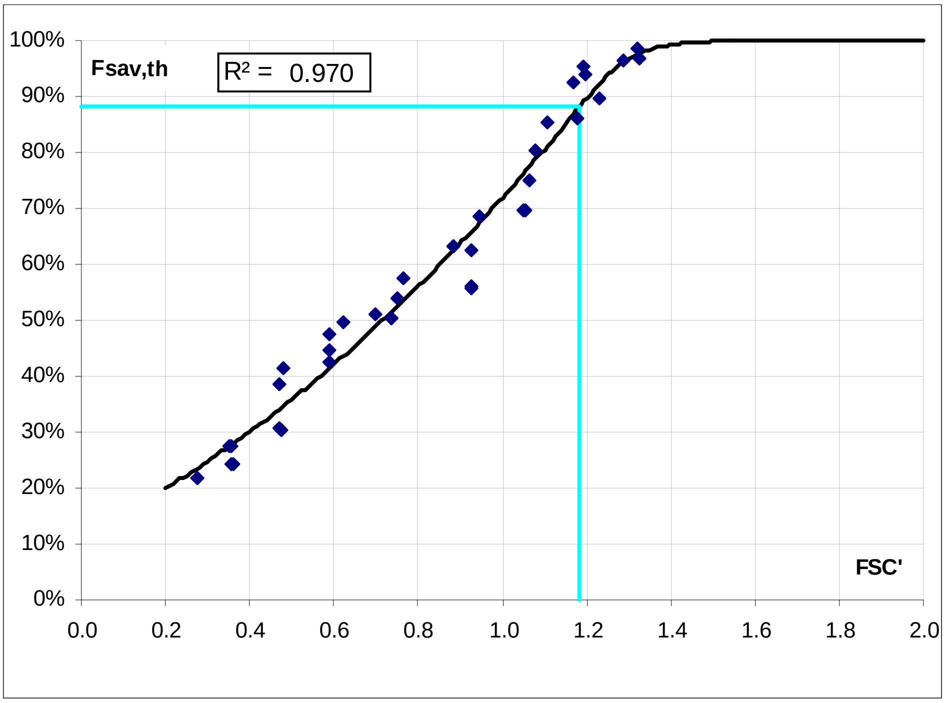



*Figure 16. Water system, variation of thermal fractional energy savings with the fractional solar consumption (FSC') for 4 climates ( Zürich, Stockholm, Barcelona and Madrid) and five loads (15, 30, 60, 100 and 100n kWh/m²a single family building) with a storage ratio of 55 and 83 l/m² collector.*

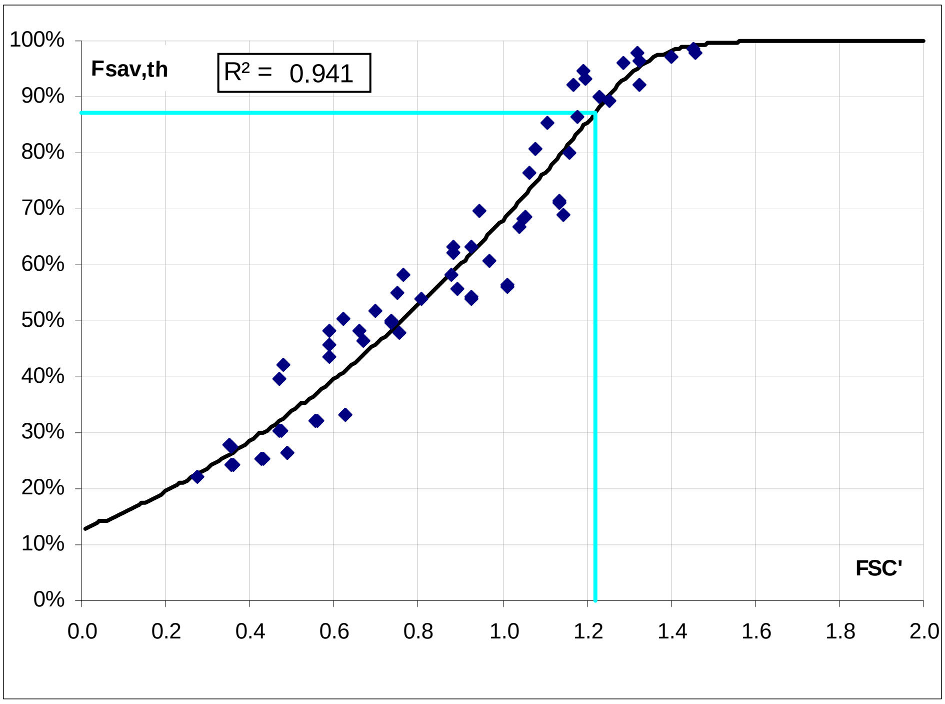



*Figure 177. Water + PCM system, variation of thermal fractional energy savings with the fractional solar consumption (FSC') for 4 climates ( Zürich, Stockholm, Barcelona and Madrid) and five loads (15, 30, 60, 100 and 100n kWh/m²a single family building).*

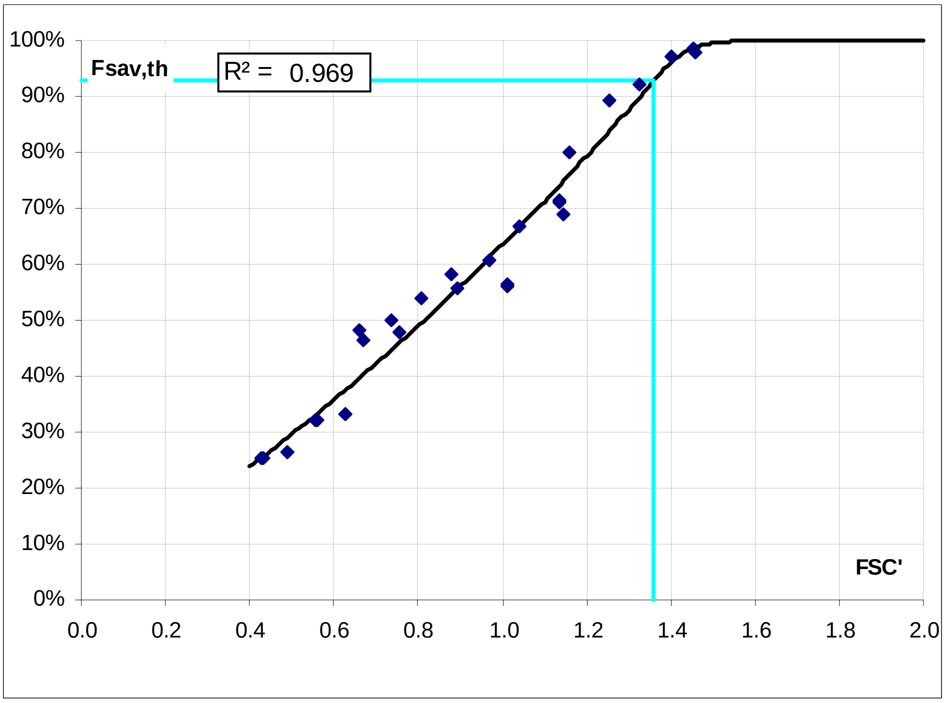



*Figure 188. Water + PCM system, variation of thermal fractional energy savings with the fractional solar consumption (FSC') for 4 climates ( Zürich, Stockholm, Barcelona and Madrid) and five loads (15, 30, 60, 100 and 100n kWh/m²a single family building) with a storage ratio of 2,7 and 3,4 kWh/m$^2$ collector.*

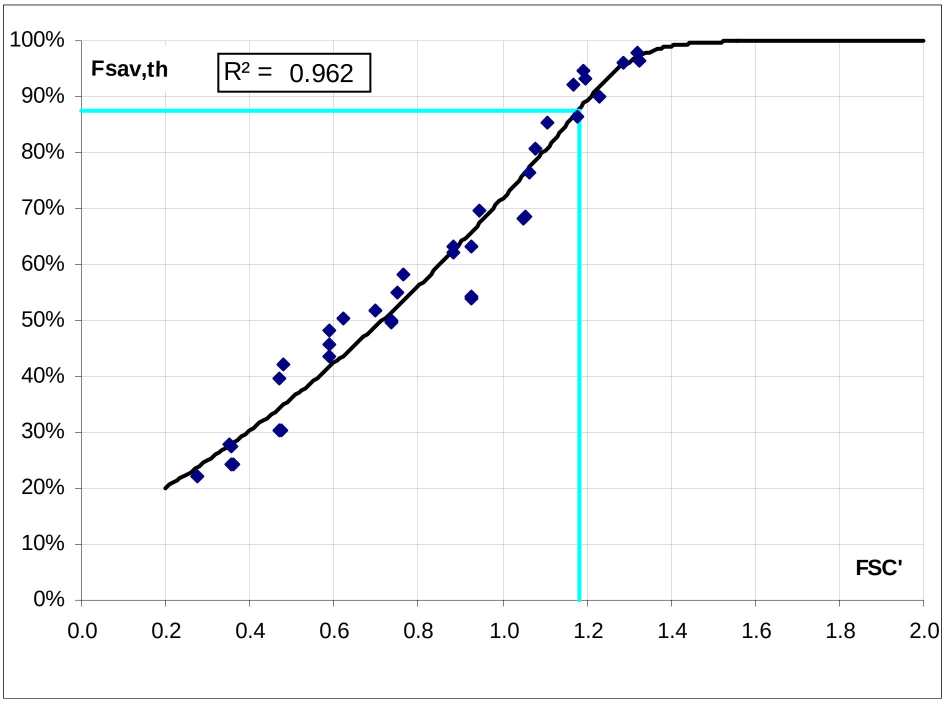



*Figure 199. Water + PCM system, variation of thermal fractional energy savings with the fractional solar consumption (FSC') for 4 climates ( Zürich, Stockholm, Barcelona and Madrid) and five loads (15, 30, 60, 100 and 100n kWh/m²a single family building) with a storage ratio of 4,5 and 6,7 kWhl/m$^2$ collector.*

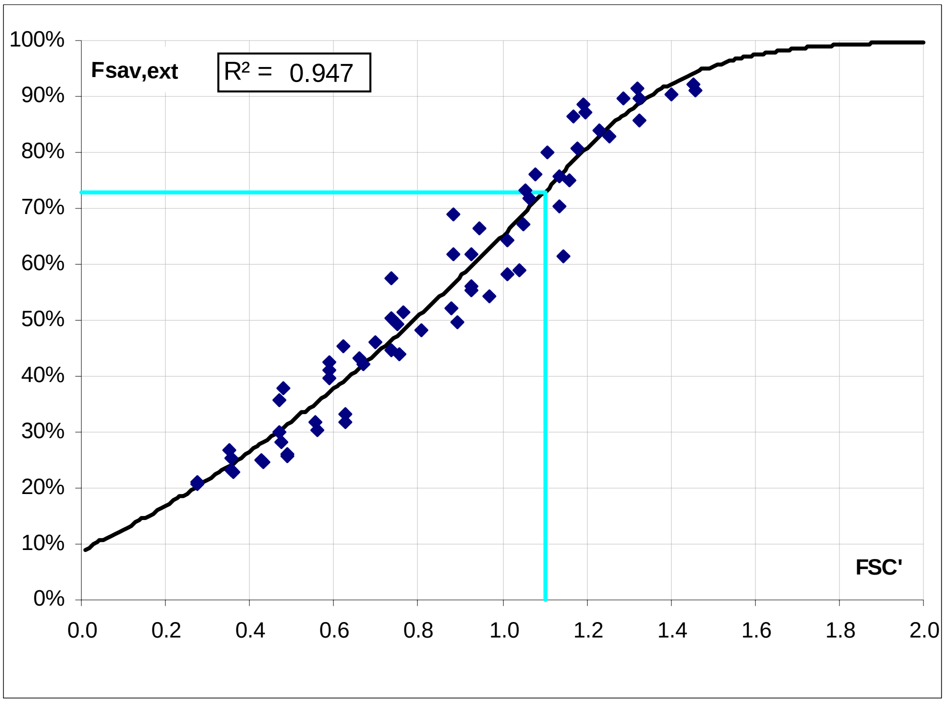



*Figure 20. Water system, variation of extended fractional energy savings with the fractional solar consumption (FSC') for 4 climates ( Zürich, Stockholm, Barcelona and Madrid) and five loads (15, 30, 60, 100 and 100n kWh/m²a single family building).*

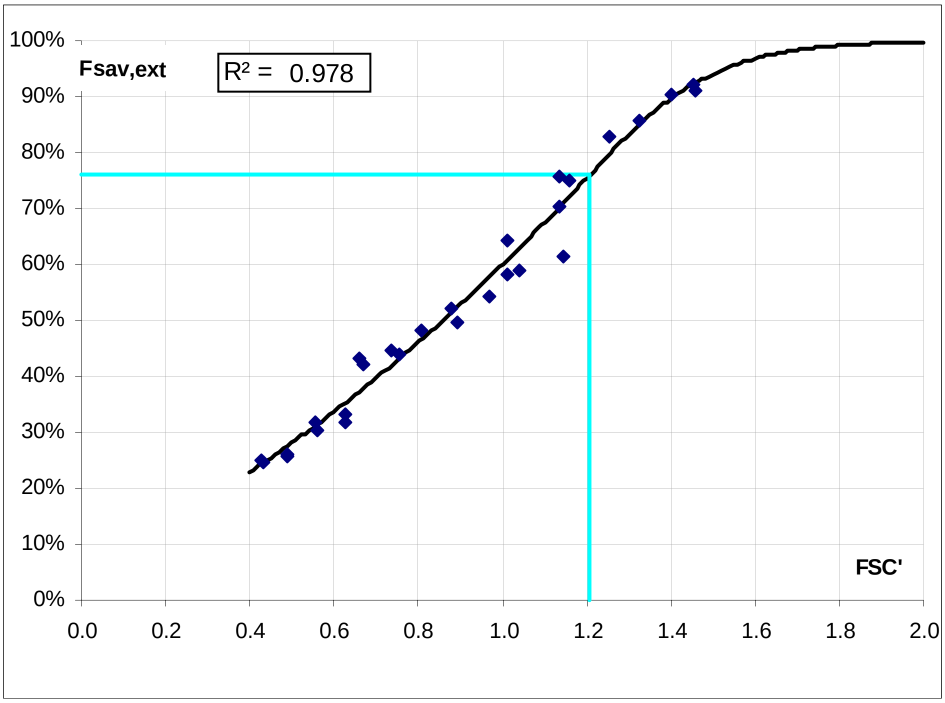



*Figure 21. Water system, variation of extended fractional energy savings with the fractional solar consumption (FSC') for 4 climates ( Zürich, Stockholm, Barcelona and Madrid) and five loads (15, 30, 60, 100 and 100n kWh/m²a single family building) with a storage ratio of 33.2 and 45.1 l/m² collector.*

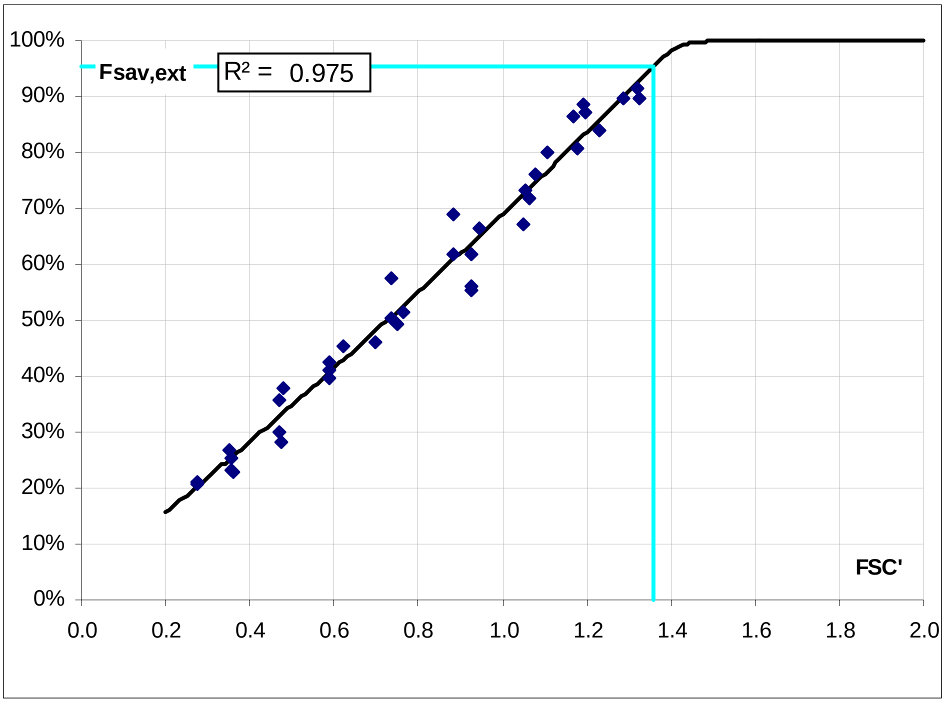



*Figure 22. Water system, variation of extended fractional energy savings with the fractional solar consumption (FSC') for 4 climates ( Zürich, Stockholm, Barcelona and Madrid) and five loads (15, 30, 60, 100 and 100n kWh/m²a single family building) with a storage ratio of 55 and 83 l/m² collector.*

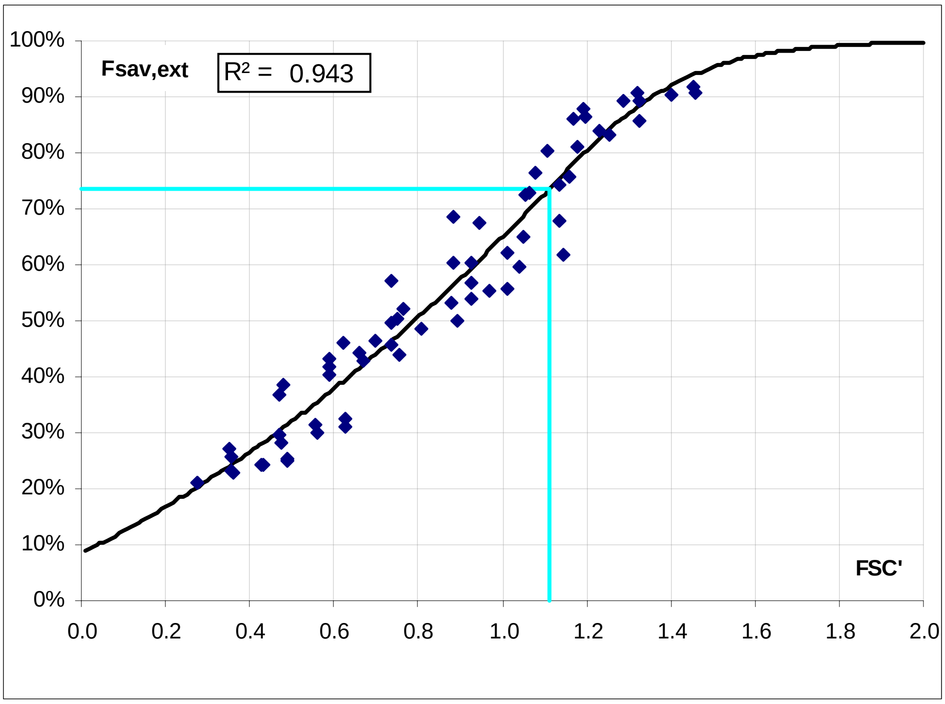



*Figure 23. Water + PCM system, variation of extended fractional energy savings with the fractional solar consumption (FSC') for 4 climates ( Zürich, Stockholm, Barcelona and Madrid) and five loads (15, 30, 60, 100 and 100n kWh/m²a single family building).*

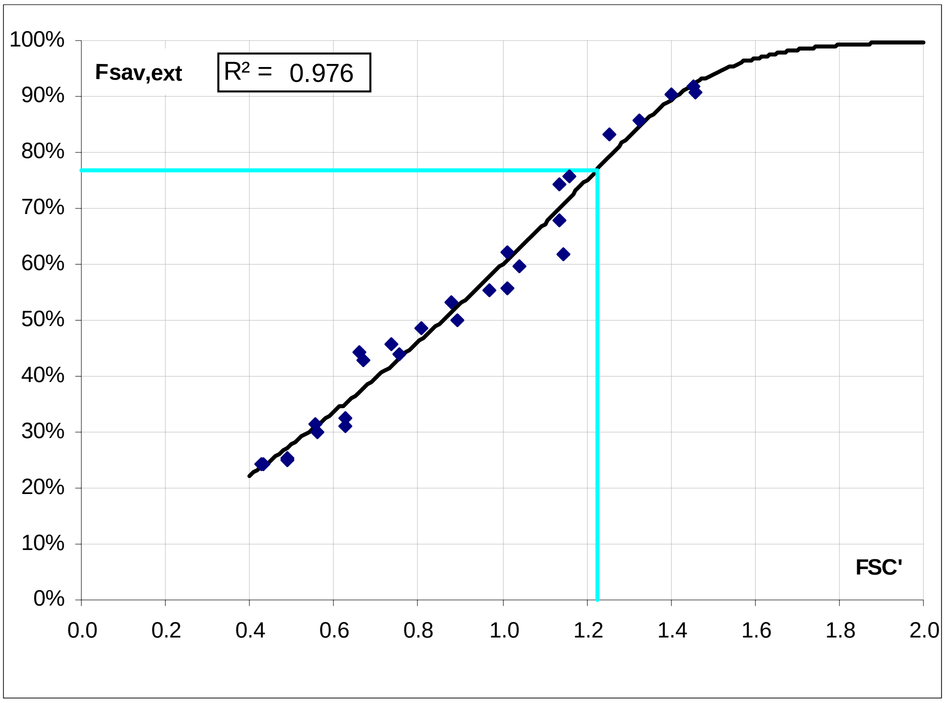



*Figure 24. Water + PCM system, variation of extended fractional energy savings with the fractional solar consumption (FSC') for 4 climates ( Zürich, Stockholm, Barcelona and Madrid) and five loads (15, 30, 60, 100 and 100n kWh/m²a single family building) with a storage ratio of 2,7 and 3,4 kWh/m$^2$ collector.*

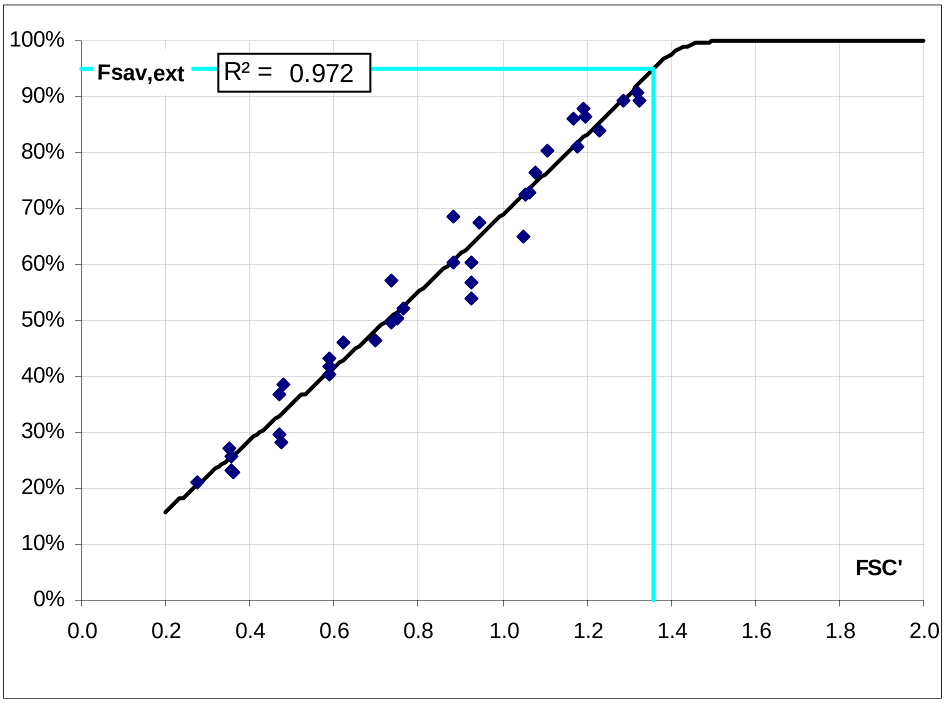



*Figure 25. Water + PCM system, variation of extended fractional energy savings with the fractional solar consumption (FSC') for 4 climates ( Zürich, Stockholm, Barcelona and Madrid) and five loads (15, 30, 60, 100 and 100n kWh/m²a single family building) with a storage ratio of 4,5 and 6,7 kWhl/m$^2$ collector.*

# 6 Lessons learned

## 6.1 Concerning simulation

It has been noticed, that the energy balance calculation is very important. In the first simulations, the global energy balance was good. In the latest simulations, where different configurations where analysed, it has been noticed that the energy was not balanced especially on the auxiliary loop. The difference is between 0 to 3 %.

In order to find the source of the mistakes, the storage tank, the auxiliary loop and the specific controller type has been tested separately.

- The type 60 "storage water tank" the energy balance was incorrect. It has been fixed in our Type 860 derived from type 60.

- The specific controller Type 889 has shown different behaviour between TRNSYS15 and TRNSYS16.

With these problem solved, the performances presented in Zurich, which showed an improvement between 6 to 8 %, are in fact less than 3%.

The energy balance of the type 860 (Type60+PCM) has shown a dependency to the inlet and outlet position. In the simulations presented in this document, the inlet and outlet position have been selected to avoid this problem, but we could not optimise these positions.

## 6.2 Concerning the system

It should be reminded that the proposed system has been analysed only from the simulation side, where we compare a water tank storage filled only with water or filled with water + PCM (paraffin RT35).

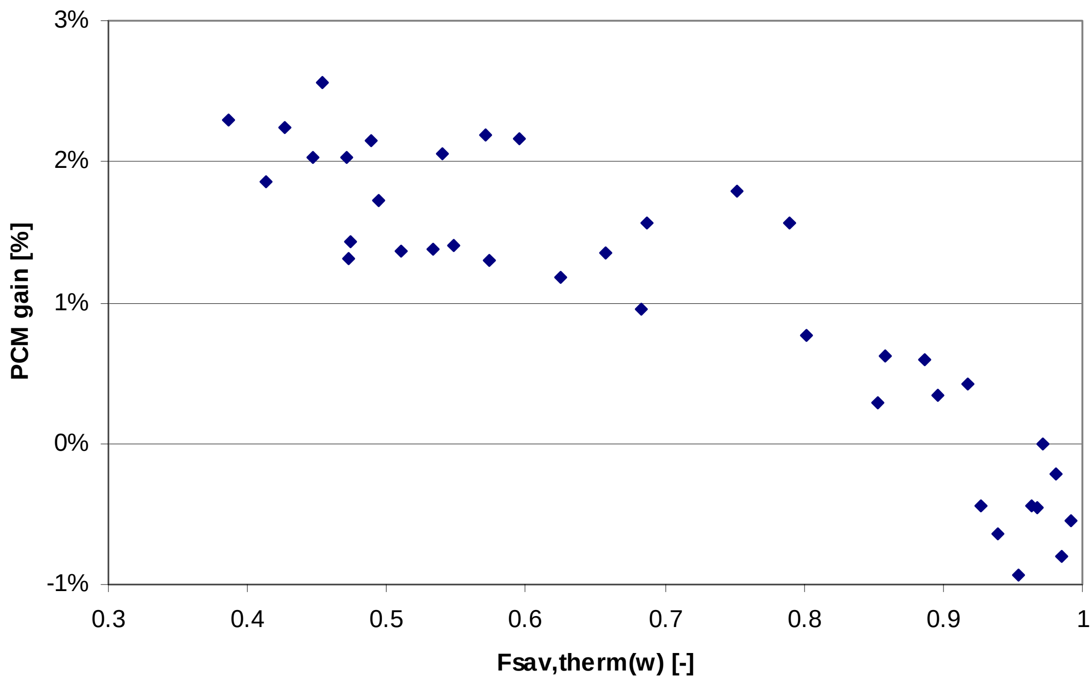



*Figure 26. Difference between pure water and water + PCM system. The PCM gain = $F_{sav,therm(W+PCM)}/F_{sav,therm(W)}$ - 1*

To evaluate the impact of the PCM on the performances, it is possible to define the energy gain between the $F_{sav,therm}$ for the tank with PCM ($F_{sav,therm(W+PCM)}$) and only with water ($F_{sav,therm\ (W)}$). If this gain is higher than 0, then the PCM brings an advantage. As it can be seen in Figure , the gain due to using PCM is low. We can also notice the decrease of the RATIO according to the increase of the $F_{sav,therm}$. But it should be remembered, that when the $F_{sav,therm}$ is high, the solar installation is oversized. As it can be seen, adding a PCM becomes less interesting when the solar system is oversized. This is due to the fact, that when oversized, the storage of heating is less relevant.

According to the additional cost of adding the PCM and the environmental impacts results described in a previous report, this system with PCM does not show a substantial benefit compare to a storage tank filled only with water.

# 7 References

Heimrath R., Haller, M., 2007, Project Report A2 of Subtask A, the Reference Heating System, the Template Solar System, A Report of the IEA-SHC Task32

Streicher W., Heimrath R., et. al., 2002, IEA-SHC -TASK 26: SOLAR COMBISYSTEMS, Subtask C, Milestone Report C 0.2 - Reference Conditions (Climate, DHW- demand, SH-demand, reference buildings, auxiliary heater, solar plant, electricity consumption), 2002

Streicher W., Heimrath R., et. al.,2002, IEA-SHC -TASK 26: SOLAR COMBISYSTEMS, Subtask C, Milestone Report C 3.1, Optimization Procedure ( reference system, penalty function, target function)

Letz T., 2007, The extended FSC procedure for larger storage sizes, internal paper Task 32

Klein S.A., 2005, TRNSYS16 reference manual

# 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 32.

## 8.1 Type 889: Heating loop and auxiliary controller

Specific type base on existing controller for the space heating loop.

### Parameters :

| | | |
|---|---|---|
| Mburner | MASS FLOW RATE INTO THE BOILER | (kg/h) |
| DT140 | DIFFERENTIAL ON/OFF OF THE BURNER | (°C) |
| Text161 | EXTERNAL REFERENCE MINIMUM TEMPERATURE | (°C) |
| Tch162 | MAXIMUM REFERENCE TEMPERATURE START HEATING | (°C) |
| DT168 | DIFFERENTIAL TEMPERATURE BOILER/HEATING T° | (°C) |
| I170 | TYPE OF BUILDING (HEAVY=3/LIGHT=1 | (-) |
| R171 | HEATING SPEED (1 OR 0) | (-) |
| Infl183 | FRACTIONAL INFLUENCE OF INT. AMB. SENSOR | (-) |
| Tecs190 | TEMPERATURE OF DHW | (°C) |
| DTecs191 | DIFFERENTIAL TEMPERATURE FOR DHW | (°C) |
| mrad | EXPONENT RADIATOR | (-) |
| mch_tot | MAX FLOW RATE OF THE HEATING LOOP | (kg/h) |
| DTchnom | DIFFERENTIAL TEMP. COME IN/RETURN HEATING | (°C) |

### Inputs :

| | | |
|---|---|---|
| Tm_cuve | TEMPERATURE IN THE MIDDLE OF THE TANK | (°C) |
| Thaut_cuve | TEMPERATURE IN THE TOP OF THE TANK (°C) | |
| Tcon_amb | ORDER TEMPERATURE FOR THE AMBIENT T° BUILDING | (°C) |
| Textn0 | OUTSIDE TEMPERATURE | (°C) |
| Tret_ext | RETURN TEMP. OF HEATING LOOP | (°C) |
| Tamb | AMBIENT TEMPERATURE | (°C) |
| Tcuve_ch | OUTLET TEMPERATURE OF THE TANK FOR HEATING | (°C) |

### Outputs :

| | | |
|---|---|---|
| Tch_2 | TEMPERATURE OF HEATING LOOP | (°C) |
| DTcheff | DIFFERENTIAL EFFECTIVE TEMPERATURE FOR SH | (°C) |
| mch_tot2 | FLOW RATE FOR HEATING LOOP | (kg/h) |
| Aux | SWITCH ON OF THE BURNER | (-) |
| TretBur | RETURN TEMPERATURE TO THE BOILER | (°C) |
| TsetBurn | SET POINT TEMPERATURE FOR THE GAS BOILER | (°C) |
| mRetTank | RETURN FLOW RATE TO THE TANK | (kg/h) |
| mRetBurn | RETURN FLOW RATE TO THE GAS BOILER | (kg/h) |
| ECS1 | DHW PRERATION MODE | (-) |

Availibility : DLL file available

## 8.2 Type 860: Water and Phase Change Material (PCM) storage tank (base on type60)

This specific type is based on the standard type60 from TRNSYS library. Please refer to TRNSYS description of this type60 for the conventional parameters, inputs and outputs. For more information see the IEA32 C5 report *Simulation model of PCM modules plunged in a water tank*.

### Parameters :

| | | |
|---|---|---|
| modelat | NUMBER OF PCM ZONE (10 MAX) | (-) |
| nodesup | NUMBER OF UPPER PCM NODE | (-) |
| nodeinf | NUMBER OF LOWER PCM NODE | (-) |
| ENTHALPY CURVE CARACTERISTIC | | |
| Hyst | HYSTERESIS DT | (K) |
| Subcool | SUBCOOLING DT | (K) |
| Rho | MEAN PCM DENSITY | (kg/m$^3$) |
| Lamb1 | RADIAL SOLID CONDUCTIVITY INTO PCM | (W/m.K) |
| Lamb1Liq | RADIAL LIQUID CONDUCTIVITY INTO PCM | (W/m.K) |
| Lamb2 | AXIAL MEAN CONDUCTIVITY INTO PCM | (W/m.K) |
| NcPCM | NUMBER OF PCM NODE | (-) |
| Ep0 | THICKNESS OF PCM CONTAINER | (mm) |
| Dia | Dimension of PCM module | (mm) |
| Contain1 | KIND OF CONTAINER (1=sphere, 2=cyl. , 3=slab) | (-) |
| Ncont | NUMBER OF CONTAINER IN A HORIZONTAL CROSS SECTION | (-) |
| Rhoc | CONTAINER DENSITY | (kg/m$^3$) |
| NcPCM | NUMBER OF PCM NODE | (-) |
| Cpc | CONTAINER CP | (J/kg.K) |
| Lamb0 | CONTAINER CONDUCTIVITY | (W/m.K) |
| KpcmAdd | ADDITIONAL DE-STRATIFICATION CONDUCTIVITY | (W/m.K) |
| PcmOutput | NUMBER OF NODE FOR PCM TEMPERATURE OUTPUT | (-) |
| Viscocin | PCM CINEMATIC VISCOSITY | (kg/m$^3$) |
| Hlimit | LIMIT ENTHALPY WHERE WE SUPPOSE TO BE LIQUID | (kJ/kg) |
| RhoLiq | PCM LIQUID DENSITY | (kg/m$^3$) |
| CpLiq | PCM LIQUID CP | (J/kg.K) |
| CoefDilat | DILATATION COEFFICIENT OF LIQUID PCM | (1/K) |
| LambLiq | PCM LIQUID LAMBDA | (W/m.K) |

### Inputs :

Idem type60

### Outputs :

| | | |
|---|---|---|
| Twater_node | WATER TEMPERATURE AT PCM LEVEL | (°C) |
| Tpcm_node | TEMPERATURE INSIDE PCM NODE | (°C) |
| PCMpower | POWER FOR EACH PCM LEVEL | (W) |
| AlphaPCM | CONVECTIVE COEFFICIENT WATER/PCM FOR EACH LEVEL | (W/m$^2$.K) |

Availibility : DLL file available