Report on Solar Combisystems Modelled in Task 26

Appendix 3: Generic System #4: DHW Tank as a Space-Heating Storage Device

A Report of IEA SHC - Task 26

Solar Combisystems

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Louise Jivan Shah

INTERNATIONAL ENERGY AGENCY
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Appendix 3:
Generic System #4: DHW Tank as a Space-Heating Storage Device

by

Louise Jivan Shah *

A technical report of Subtask C

*Technical University of Denmark
BYG.DTU
Department of Civil Engineering
Build. 118
DK-2800 Lyngby
www.byg.dtu.dk

Preface

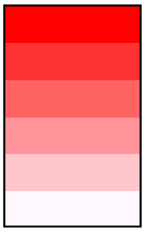
The report is a part of the technical deliveries for IEA Task 26 Solar Combisystems, Subtask C. The report deals with TRNSYS simulations of one of the two Danish systems in the task work.

The Danish participation in Task 26 was financed by The Danish Energy Authority.

Contents

1 General description of System #4 DHW Tank as a Space-Heating Storage Device

Non-Stratified Storage (Denmark)



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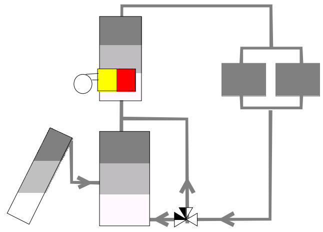


Main features

This system is derived from a standard solar domestic hot water system, in which the collector area has been oversized, in order to be able to deliver energy to an existing space heating system. This is made through an extra heat exchanger included in the DHW tank. The system can be used to deliver energy to an existing space heating system. Heat coming from the solar collector is delivered to a DHW tank, which acts also as a small buffer tank for space heating. The DHW storage is equipped with three internal heat exchangers: the solar one in the bottom of the tank, the auxiliary one at the top, and an intermediate included in the return pipe of the space heating loop. A three-way valve conducts the fluid coming from the space heating loop either to the heat exchanger, or directly to the auxiliary boiler.

Heat management philosophy

The controller does not manage the auxiliary part of the system. If the temperature at the collector outlet is higher than the temperature at the bottom of the tank, the pump of the solar loop works. The three-way valve is managed so as to deliver solar energy to the space heating loop, i.e. when the temperature in the middle of the tank is higher than the temperature at the return temperature from the space heating loop. When the hot water temperature is too low, auxiliary heat is delivered to the tank through the three-way valve.

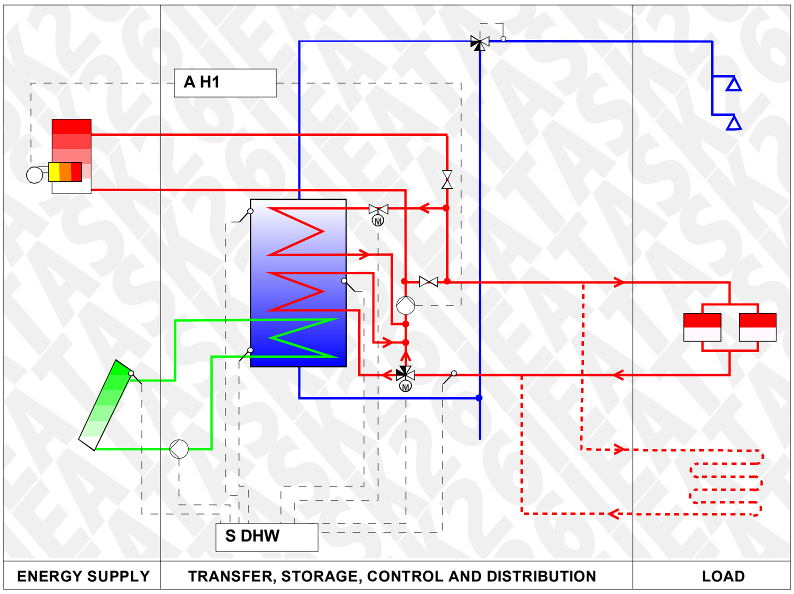


Figure 1: System design.

Specific aspects

Solar heat used for space heating is stored in the domestic hot water tank.

Influence of auxiliary energy source on system design and dimensioning
This system can work with any auxiliary energy (gas, fuel, wood, district heating). It could be also used with separate electric radiators.

Cost (range)
A typical system with 15 m² of solar collectors and a 800 litre storage unit costs about 7 000 EUR. This amount only includes the solar part (collectors, storage tank, controller and heat exchanger, installation), since the auxiliary part (boiler, radiator circuit) already exists. Total cost for complete heating system with solar is 15 600 EUR, and reference cost for complete heating system without solar is 9 300 EUR.

Market distribution
This system is quite new in Denmark. Only one company markets this system, with a total collector area in operation of 100 m². The system is marketed by the manufacturer and is available anywhere in Denmark from the nearest installer (400-800 potential installers).

Manufacturer: Batec A/S

2 Modelling of the system

2.1 TRNSYS model

The combisystem is modelled in TRNSYS 14.2 [1] and the model includes collectors, collector loop, storage, auxiliary boiler, building, radiator, pumps, and control systems. Figure 2 shows a diagram of the system model, and each component is described in greater detail in the next section.

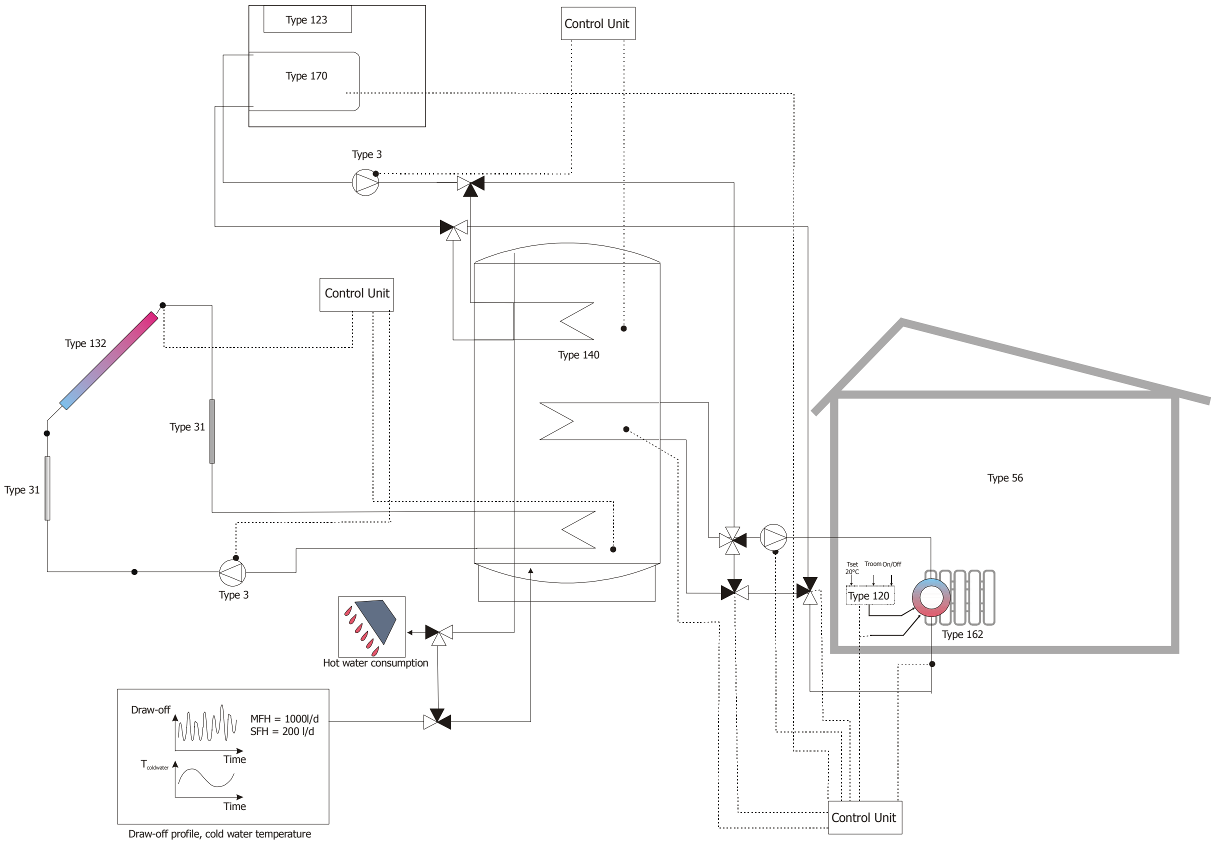


Figure 2: Diagram of System #4 modelled in TRNSYS 14.2.

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

The simulations will start out with investigations of a “base case” system with a specific collector area, tank volume, insulation thickness, heat exchanger size etc. In the following subsections, the most important model components and parameters of the base case system are described.

2.2.1 Collector

For the later comparison of different combisystem concepts, it is an advantage if all the systems are modelled with similar collectors. Therefore, the combisystem is modelled with a standard flat plate collector with a reference efficiency expression as described in Table 1. The base case system has a collector area of 15 m² and, as the system is not a low flow system, a specific mass flow rate through the collectors is 72 l/m²/h. The collector is modelled with the non-standard TRNSYS Type 132.

Collector	η_0	0.8 -
	a_1	3.5 W/m²-K
	a_2	0.015 W/m²-K²
	inc. angle modifier (50°)	0.9 -
	Area	15 m²
	Specific mass flow	72 l/m²h

Table 1: Collector data (as defined in [4]).

2.2.2 Pipes between Collector and Storage

The geometry and insulation thickness of the pipes between collector and tank is given in Table 2. For the heat loss calculations, an average surrounding temperature of 15 °C is given. The pipes in the collector loop are modelled with TRNSYS Type 31.

Collector loop	Length, tank to collector (cold side)	15 m
	Length, tank to collector (hot side)	15 m
	Inner diameter	0.02 m
	Outer diameter	0.022 m
	Insulation thickness	0.02 m
	Insulation thermal conductivity	0.042 W/mK
	Heat transfer medium	Glycol (40%)/Water

Table 2: Collector loop data (as defined in [4]).

2.2.3 Storage

The base case storage tank has a total volume of 750 l. The height of the storage is defined from following equation as defined in [4].

$$H=\mathrm{Max}[\mathrm{Min}\{2.2,1.78+0.39\cdot\ln(V)\},0.8]$$

where,

H is the storage height [m]

V is the storage volume [m³]

For this storage, the equation gives a storage height of 1.67 m and thus a diameter of approximately 0.76 m.

The top and sides of the base case storage tank is insulated with 0.15 m insulation material with a thermal conductivity of 0.042 W/mK. The bottom is not insulated. As theoretical calculated heat losses are typical smaller than actual measured heat losses, a correlation constant is multiplied with the theoretical calculated heat loss [4]:

$$UA_{real}=C_{corr}\cdot UA_{theory}$$
$$C_{corr}=Max[1.1,(1.5-V/10)]$$

where,

UA_{real} is the adjusted heat loss coefficients for the storage top/side/bottom [W/K]
C_{corr} is the correlation constant [-]
UA_{theory} is the theoretical heat loss coefficients for the storage top/side/bottom [W/K]
V is the storage volume [m³]

For this storage, the equation gives C_{corr} = 1.425.

The vertical thermal conductivity is defined from the following equation [4]:

$$\lambda_{vertical}=Max[0.7,(1.3-V/10)]$$

where

$\lambda_{vertical}$ is the vertical thermal conductivity [W/mK]
V is the storage volume [m³]

For the base case storage $\lambda_{vertical}$ equals 1.225 W/mK.

As shown in Figure 1, the storage tank includes three internal heat exchangers: Heat exchanger no. 1 is used in the solar collector loop. It is a serpentine heat exchanger with a heat transfer coefficient of 750 W/K and it is placed in the lowest part of the storage tank. Heat exchanger no. 2 is used in the space heating loop. It is a serpentine heat exchanger with a heat transfer coefficient of 750 W/K and it is placed in the middle part of the storage tank. Heat exchanger no. 3 is used in the auxiliary heating loop. It is also a serpentine heat exchanger with a heat transfer coefficient of 750 W/K and it is placed in the top part of the storage tank.

The storage tank is modelled with TRNSYS Type 140 (version 1.95) [2] and the storage data are summarised in Table 3.

Storage tank	Total volume	0.75 m³
	Height	1.67 m
	Diameter	0.76 m
	Auxiliary volume	0.15 m³
	Insulation thickness, top	0.15 m
	Insulation thickness, sides	0.15 m
	Insulation thickness, bottom	0 m
	Thermal conductivity of insulation material	0.042 W/mK
	Vertical thermal conductivity	1.225 W/mK
	Solar HX inlet [1)]	0.3
	Solar HX outlet [1)]	0.05
	Space heating HX inlet [1)]	0.4
	Space heating HX outlet [1)]	0.7
	Auxiliary HX inlet [1)]	0.8
	Auxiliary HX outlet [1)]	1
	Solar HX heat transfer capacity	750 W/K

Space heating HX heat transfer capacity	750 W/K
Auxiliary HX heat transfer capacity	750 W/K
Cold water inlet [1)]	0
Hot water outlet [1)]	1
Position of collector control temperature sensor [1)]	0.02
Position of space heating control temperature sensor [1)]	0.4
Number of nodes	30
Charging and discharging	Non-stratified

Table 3: Storage tank data. [1)]Relative height: Storage bottom = 0, Storage top = 1.

2.2.4 Boiler

The boiler in the system is a modulating condensing gas boiler. The burner has a nominal power of 15 kW and modulates in the range of 25%-100%. For the heat loss calculations, a surrounding temperature of 15 °C is used.

The gas boiler is modelled with TRNSYS non-standard Type 170 (version 3.00) [3] and it is controlled with TRNSYS non-standard Type 123. The boiler data are summarised in Table 4.

Boiler	Nominal power	15 kW
	Set supply temperature for domestic hot water	65°C
	Fuel type[2)]	Natural gas, high
	Ambient temperature in the boiler house	15°C
	Operation standby temperature of the boiler	30°C
	Hysteresis temperature difference for standby temperature	5 K
	Maximum main water temperature of the boiler	90°C
	Air surplus number (λ) [2)]	1.2
	Modulation range	25%-100%
	Mass of the boiler water	7.5 kg
	Temperature difference between flue gas and return temperature in the heat exchanger[2)]	10 K
	Maximum losses through radiation related to the maximum heat performance[2)]	3.5 %
	Standby losses related to the maximum heat performance[2)]	1.5 %
	Mode[2)]	10
	Minimum running time	1 min
	Minimum stand still time	1 min

Table 4: Boiler data as defined in [4] . [2)] See [3] for details.

2.2.5 Building

The combisystem will be modelled together with a full single-family house with either a low, a medium, or a high space heating demand. The three houses have the same geometry but different building physics data were defined in a way that the specific yearly space heat demand for Zurich climate amounts to 30, 60 and 100 kWh/m² per year.

The building is modelled with TRNSYS type 56 and an overview of the building properties is given in Table 5.

Building	Specific space heating demand for Zurich climate	**30 kWh/m² per year**
	Area	140 m²
	Total window area (East: 4m², West: 4m², North: 3m², South: 12m²)	23 m²
	Window U-value	0.4 W/m²K
	Window g-value	0.408
	External walls, U-value	0.135 W/m²K
	Roof, U-value	0.107 W/m²K
	Ground floor, U-value	0.118 W/m²K
Building	Specific space heating demand for Zurich climate	**60 kWh/m² per year**
	Area	140 m²
	Total window area (East: 4m², West: 4m², North: 3m², South: 12m²)	23 m²
	Window U-value	1.4 W/m²K
	Window g-value	0.589
	External walls, U-value	0.342 W/m²K
	Roof, U-value	0.227 W/m²K
	Ground floor, U-value	0.196 W/m²K
Building	Specific space heating demand for Zurich climate	**100 kWh/m² per year**
	Area	140 m²
	Total window area (East: 4m², West: 4m², North: 3m², South: 12m²)	23 m²
	Window U-value	2.8 W/m²K
	Window g-value	0.755
	External walls, U-value	0.508 W/m²K
	Roof, U-value	0.494 W/m²K
	Ground floor, U-value	0.546 W/m²K

Table 5: Building properties as defined in [5].

2.2.6 Heat distribution

The space heat distribution system is defined as an ambient temperature controlled radiator system with thermostatic valves adjusting the mass flow according to variable inner heat loads.

The radiator is modelled with TRNSYS non-standard Type 162 and it is controlled with a PID-controller, TRNSYS non-standard Type 120. Table 6 lists the design temperatures and the nominal power for the radiator system for the different buildings and climates.

Climate	Building	Nom. Power [W]	Design flow temperature [°C]	Design return temperature [°C]	Design ambient temperature [°C]
Stockholm	30 kWh/m²/year	3480	35	30	-17
Stockholm	60 kWh/m²/year	6160	40	35	-17
Stockholm	100 kWh/m²/year	9050	60	50	-17
Zurich	30 kWh/m²/year	2830	35	30	-10
Zurich	60 kWh/m²/year	4950	40	35	-10
Zurich	100 kWh/m²/year	7290	60	50	-10
Carpentras	30 kWh/m²/year	2460	35	30	-6
Carpentras	60 kWh/m²/year	4260	40	35	-6
Carpentras	100 kWh/m²/year	6320	60	60	-6

Table 6: Radiator data ([4]).

2.2.7 Control strategy

There are four controllers in the system: One for the collector loop, one for the space heating system, one for setting the domestic hot water priority and one for setting the minimum running time and standstill time of the burner. Table 7 describes the different controllers:

Collector control	Model (on/off controller)	Type 2
	Start temperature difference	10 K
	Stop temperature difference	2 K
Space heating control	Model (PID controller)	Type 120
	Width of PID-band	3 K
	Proportional gain in PID-band	0.8
	Integral gain in PID-band	0.05
	Differential gain	0
DHW priority control	Model (on/off controller)	Type 2
	Set temperature of hot water	50.5°C
	Hysteresis	+- 5 K
Burner running time control	Model	Type 123
	Minimum running time	1 min
	Minimum stand still time	1 min

Table 7: Controller settings.

2.3 Validation of the system model

Since only very few systems have been installed and none have been measured, the simulation model has not been validated against measurements.

3 Simulations for testing the library and the accuracy

TRNSYS is an open source code where the user can modify sub-models and compile them into a user specific dynamic link library called TRNLIB.DLL. In the Task 26 subtask C work, all users from all countries had to use similar TRNLIB.DLL in order to be able to compare the results. Therefore, a TRNLIB.DLL comparison with a reference DLL file had to be performed. This comparison is described in the following section.

3.1 Result of the TRNLIB.DLL check

The local TRNLIB.DLL was checked by calculating the three single-family reference buildings for all three climates. The three tables below show the results calculated with the reference TRNLIB.DLL (top table), the results calculated with the local TRNLIB.DLL (middle table) and the differences in percents (bottom table).

In the table, Q_{SH} is the space heating demand, Q_{DHW} is the energy demand for domestic hot water, $E_{BOILER,REF}$ is the final energy consumption of the natural gas boiler, $E_{TOTAL,REF}$ is the combined total energy consumption of the reference building (=gross gas consumption + gross electrical energy consumption) and Q_{pen} is the penalty (see [4] for details).

From the tables it is clear that the local TRNLIB.DLL calculate the expected results for the single family houses. Thus, the local TRNLIB.DLL is used for the calculations.

Results - Reference Buildings

Thomas Letz, October 16, 2001 - Richard Heimrath, April 21, 2002

	Q_{SH} / kWh			Q_{DHW} / kWh	$E_{BOILER,REF}$ / kWh			$E_{TOTAL,REF}$ / kWh			Qpen / kWh		
	SFH 30	SFH 60	SFH 100	SFH	SFH 30	SFH 60	SFH 100	SFH 30	SFH 60	SFH 100	SFH 30	SFH 60	SFH 100
Carpentras	1565	3587	6925	2723	5802	8180	12107	6738	9342	13521	27338	31807	28129
Zürich	4319	8569	14283	3040	9414	14415	21137	10802	15909	22743	7101	6208	3766
Stockholm	6264	12227	19773	3122	11800	18784	27693	13313	20438	29444	6247	5091	2453

Results - Reference Buildings

Louise Jivan Shah, August 19, 2002

	Q_{SH} / kWh			Q_{DHW} / kWh	$E_{BOILER,REF}$ / kWh			$E_{TOTAL,REF}$ / kWh			Qpen / kWh		
	SFH 30	SFH 60	SFH 100	SFH	SFH 30	SFH 60	SFH 100	SFH 30	SFH 60	SFH 100	SFH 30	SFH 60	SFH 100
Carpentras	1568	3590	6922	2723	5805	8184	12100	6741	9341	13520	27610	32140	28460
Zürich	4314	8563	14270	3040	9409	14410	21120	10800	15900	22730	7214	6326	3849
Stockholm	6260	12190	19760	3122	11790	18780	27680	13310	20430	29430	6350	5195	2518

Difference

Louise Jivan Shah, August 19, 2002

	Q_{SH} / kWh			Q_{DHW} / kWh	$E_{BOILER,REF}$ / kWh			$E_{TOTAL,REF}$ / kWh			Qpen / kWh		
	SFH 30	SFH 60	SFH 100	SFH	SFH 30	SFH 60	SFH 100	SFH 30	SFH 60	SFH 100	SFH 30	SFH 60	SFH 100
Carpentras	-0.19%	-0.08%	0.04%	0.00%	-0.05%	-0.05%	0.06%	-0.04%	0.01%	0.01%	-0.99%	-1.05%	-1.18%
Zürich	0.12%	0.07%	0.09%	0.00%	0.05%	0.03%	0.08%	0.02%	0.06%	0.06%	-1.59%	-1.90%	-2.20%
Stockholm	0.06%	0.30%	0.07%	0.00%	0.08%	0.02%	0.05%	0.02%	0.04%	0.05%	-1.65%	-2.04%	-2.65%

Table 8: Top table: Reference building results calculated with the reference TRNLIB.DLL. Middle table: Reference building results calculated with the local TRNLIB.DLL. Bottom table: The differences in percents.

3.2 Results of the accuracy and the timestep check

It was decided in the task work that the minimum running time and standstill time for the gas burner should be 1 minute. Therefore, the maximum timestep can be only 1 minute and this value is kept for all simulations. The accuracy of the simulations was investigated by varying the convergence and integral tolerances from 0.5 to 0.0005.

Table 9 shows the results of the accuracy check. In the table, ε is defined as:

$$\varepsilon = \frac{F_{save,therm}(i) - F_{save,therm}(i-1)}{F_{save,therm}(i-1)} \cdot 100\% \qquad \textit{with}$$

$$f_{sav,therm} = 1 - \frac{\frac{Q_{boiler}}{\eta_{boiler}} + \frac{Q_{el.heater}}{\eta_{el.heater}}}{\frac{Q_{boiler,ref}}{\eta_{boiler,ref}}} = 1 - \frac{E_{aux}}{E_{ref}}$$

where *i* is the run number defined in the table. It was decided in the task work that ε should be less than 0.01.

Further, the <u>energy imbalance,</u> EI, is defined as:

$$\begin{aligned} EI &= \textit{Energy into system} \div \textit{Energy out of system} \\ &= \textit{Energy supplied from gas boiler to heating media} \\ &\quad + \textit{Energy supplied from collector loop to storage tank} \\ &\quad \div \textit{Space heating consumption} \\ &\quad \div \textit{DHW consumption} \\ &\quad \div \textit{Heat loss from storage} \end{aligned}$$

In addition, the relative energy imbalance, REI, is defined as:.

$$EI = \frac{EI}{\textit{Energy into system}} \cdot 100\%$$

I [run no.]	Convergence Tolerance [-]	Integral Tolerance [-]	Time Step [h]	$F_{save,therm}$ [%]	ε [%]	Energy imbalance [kWh]	Relative energy imbalance [%]
1	0.05	0.05	1/60	23.1	-	755	5.42
2	0.01	0.01	1/60	29.9	29.43	138	1.03
3	0.005	0.005	1/60	30.6	2.32	67	0.50
4	0.001	0.001	1/60	31.3	2.20	21	0.16
5 crashed	0.0005	0.0005	-	-	-	-	-

Table 9: Influence of the TRNSYS convergence and integral tolerances.

It can be seen in the table that ε does not meet the demands. However, the low energy imbalance for run number 4 indicates that the accuracy for this tolerance is sufficient.

4 Sensitivity Analysis and Optimisation

4.1 Presentation of results

In this section, a sensitivity analysis of the combisystem is performed. The sensitivity analysis is performed for Zurich climate and for the building with the 60 kWh/m²/year heating demand.

The influence of the different systems parameters is evaluated by two fractional energy savings and a fractional savings indicator:

Fractional thermal energy savings:

$$f_{sav,therm} = 1 - \frac{\frac{Q_{boiler}}{\eta_{boiler}} + \frac{Q_{el.heater}}{\eta_{el.heater}}}{\frac{Q_{boiler,ref}}{\eta_{boiler,ref}}} = 1 - \frac{E_{aux}}{E_{ref}}$$

with:

$\eta_{el.heater}$ = 40% for systems that do **not** apply solely renewable energy sources

$\eta_{el.heater}$ = 90% for systems that apply solely renewable electrical energy sources

Extended fractional energy savings:

$$f_{sav,ext} = 1 - \frac{\frac{Q_{boiler}}{\eta_{boiler}} + \frac{Q_{el.hetaer}}{\eta_{el.heater}} + \frac{W_{par}}{\eta_{el}}}{\frac{Q_{boiler,ref}}{\eta_{boiler,ref}} + \frac{W_{par,ref}}{\eta_{el}}} = 1 - \frac{E_{total}}{E_{total,ref}}$$

with:

$\eta_{el.heater}$ = 40% for systems that do **not** apply solely renewable energy sources

$\eta_{el.heater}$ = 90% for systems that apply solely renewable electrical energy sources

η_{el} = 40% for all systems

Fractional savings indicator:

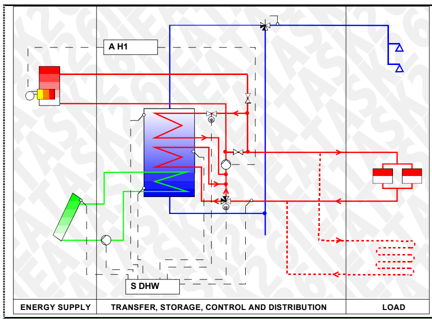
$$f_{si} = 1 - \frac{E_{total} + Q_{penalty,red}}{E_{total,ref}}$$

All definitions are described in detail in [4].

4.1.1 Sensitivity analysis

A quick overview of the base case parameters is given in Table 10 and in Table 11 a summary of the investigated parameters including their influence on the system performance is given.

Figure 3 – Figure 20 show the results for each parameter analysis and the results are if necessary commented below the figures.



#4 DHW TANK AS A SPACE-HEATING STORAGE DEVICE			
Main parameters (Base Case):			
Building:	*SFH 60 kWh/m²a*	Storage Volume:	*0.75 m³*
Climate:	*Zurich*	Storage height	*1.67 m*
Collector area:	*15 m²*	Thermal insulation, Top	*15 cm*
Collector type:	*Standard Flat Plate*	Thermal insulation, Side	*15 cm*
Specific flow rate (Collector)	*72 kg/m²-h*	Thermal insulation, Bottom	*0 cm*
Collector azimuth/tilt angle	*0 / 45°*	Nominal auxiliary heating rate	*15 kW*
Collector upper/lower dead band	*10K / 2K*	Heat Exchanger:	*750 W/K*
Solar HX inlet [1)]	0.3	Solar HX outlet [1)]	0.05
Space heating HX inlet [1)]	0.4	Space heating HX outlet [1)]	0.7
Auxiliary HX inlet [1)]	0.8	Auxiliary HX outlet [1)]	1
Simulation parameter:		Storage nodes	*30*
Time step	*1/60 h*	Tolerances Integration Convergence	*0.001 / 0.001*

Table 10: Main parameters for the base case system.

Summary of Sensitivity Parameters		
Parameter	Variation	[1]Variation in $f_{sav,ext}$
Base Case	-	24.9%
Collector size [m²] (fixed store size (0.75 m³)	5 – 25	16.4 – 26.8%
Collector Size [m²] (fixed store spec. vol. 0.05 m³/m²)	5 – 25	14.3 – 29.3%
Store Size [m³] (fixed collector area of 15 m²)	0.5 – 1.250	18.6 – 25.8%
Collector Azimuth [°] (fixed tilt of 60°)	-90 – 90	19.1 – 24.9%
Collector Tilt [°] (fixed azimuth of 0°)	0 – 75	19.8 – 25.2%
[2]Boiler Outlet Rel. Height [-]	0.5 – 0.9	22.0 – 25.9%
Auxiliary Heat Exchanger UA [%] (variation from BC value)	50 – +200	25.0 – 25.2%
Collector Heat Exchanger UA [%] (variation from BC value)	50 - +200	23.9 – 25.6%
Space Heating Heat Exchanger UA [%] (variation from BC value)	50 - +200	24.7 – 25.1%
[3]Store Insulation: top [cm]	5 – 25	24.6 – 25.1%
[3]Store Insulation: sides [cm]	5 – 25	23.8 – 25.5%
[3]Store Insulation: bottom [cm]	0 – 25	22.9 – 25.7%
[3]Store Insulation: whole store [cm]	5 – 25	21.5 – 26.4%
Collector Controller dT_{start} [K] (dTstop = 2 K)	5 – 30	24.7 – 25.2%
DHW set temperature [°C]	40 – 60	23.9 – 26.7%
Collector Controller Sensor Rel. Height [-]	0.02 – 0.3	24.9 – 26.5%
Space heating Controller Sensor Rel. Height [-]	0.4 – 0.7	24.7 – 24.9%
Climate (60 kWh SFH – Base Case)	Carp. / Zur. / Stock.	43.7% / 24.9% / 21.9%
Burner switched off during summertime		25.6%

Table 11: Summary of the sensitivity analysis.

[1] The variation in 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.

[2] The thermostat settings for store charging and electrical heater were NOT changed for these variations. Adjusting the setting to just meet the demand of the period with the highest load would probably lead to different results.

[3] The insulation has a conductivity of 0.042 W/m-K and has a correction factor for “imperfection” of C_{corr}=Max[1.1,(1.5-V/10)].

Sensitivity parameter:	Collector size [m²] (fixed store size 0.75 m³)	5 – 25 m²

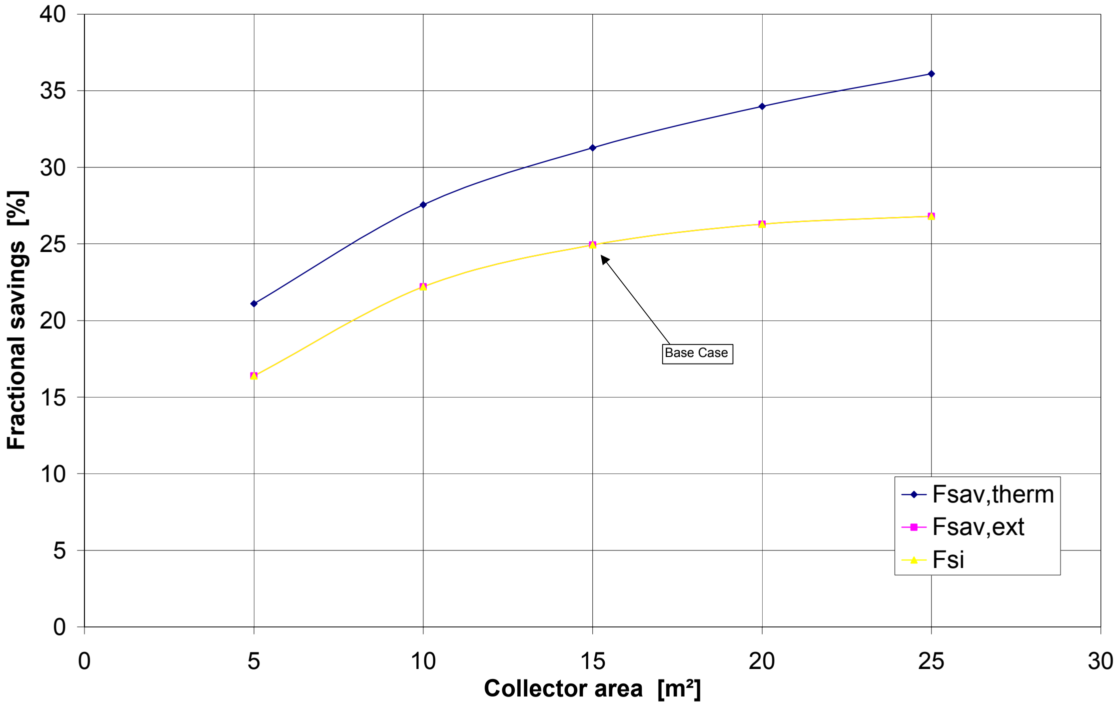


Figure 3. Variation of fractional energy savings with collector size with fixed store volume of 0.75 m³.

Differences from Base Case
The collector heat exchanger UA-value and the space heating heat exchanger UA-value are varied with the collector area in the following way:

$$UA_{HX} = A_{collector} \cdot 50 \quad [W/K]$$

Description of Results
As expected, the fractional savings increase with increasing collector area. Further it seems that there is not much gained by having larger than 15 m² of collectors. No penalties occurred for the settings so $f_{si} = f_{sav,ext}$.

Comments
None.

Sensitivity parameter:	Collector Size [m2] (fixed spec. store vol. 0.05 m^3/m^2)	5 – 25 m^2

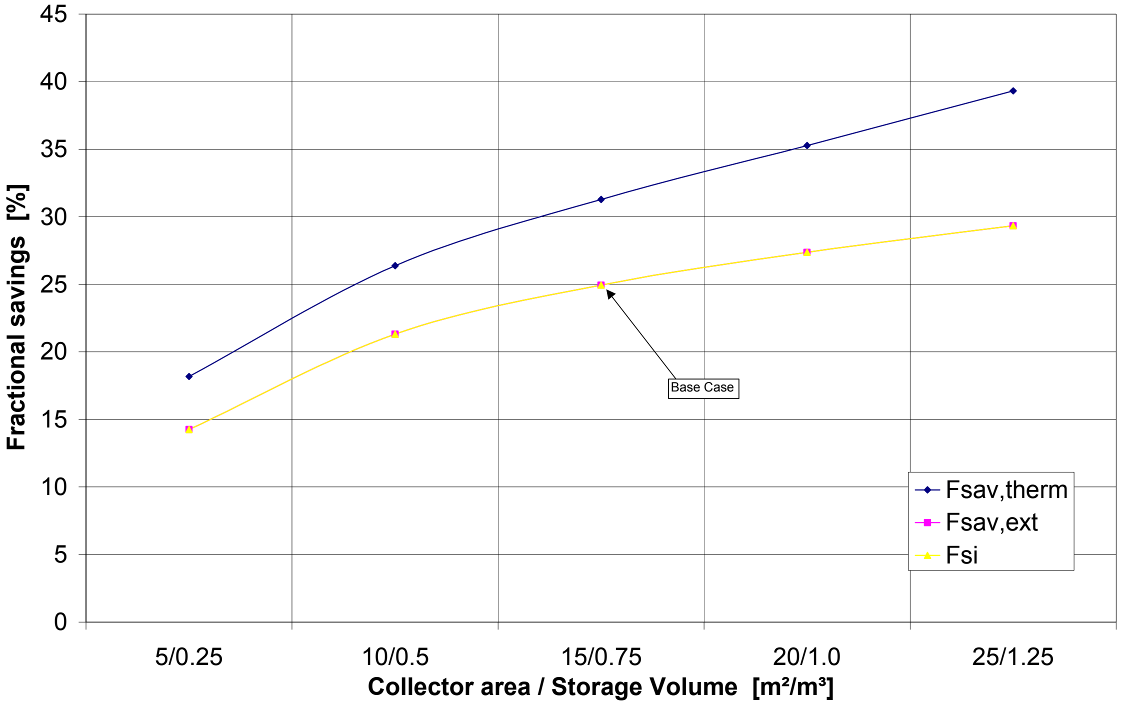


Figure 4. Variation of fractional energy savings with collector size with a fixed specific store volume of 0.05 m^3/m^2.

Differences from Base Case

- The height for the outlet of the auxiliary heat exchanger was varied so that the volume heated by the auxiliary was always the same (0.15 m^3).
- The height of the store is calculated with the following equation: $H=Max[Min\{2.2,1.78+0.39\cdot ln(V)\},0.8]$ where H is the storage height [m] and V is the storage volume [m³].
- The heat loss coefficient for the store varied using equations for the area of the relevant section. In addition, a volume sensitive “imperfection” factor, C_{corr}, was used to multiply the theoretical values: $C_{corr}=Max[1.1,(1.5-V/10)]$ where V is the storage volume [m³].
- The vertical thermal conductivity is varied by the following equation: $\lambda_{vertical}=Max[0.7,(1.3-V/10)]$.

Description of Results

As expected, the fractional savings increase with increasing collector area. Further, for collector areas larger than 15 m² the parasitic energy consumption increase rapidly. No penalties occurred for the settings so $f_{si} = f_{sav,ext}$.

Comments

None.

Sensitivity parameter:	Store Size [m3] (fixed collector area of 15 m^2)	0.25 – 1.25 m^3

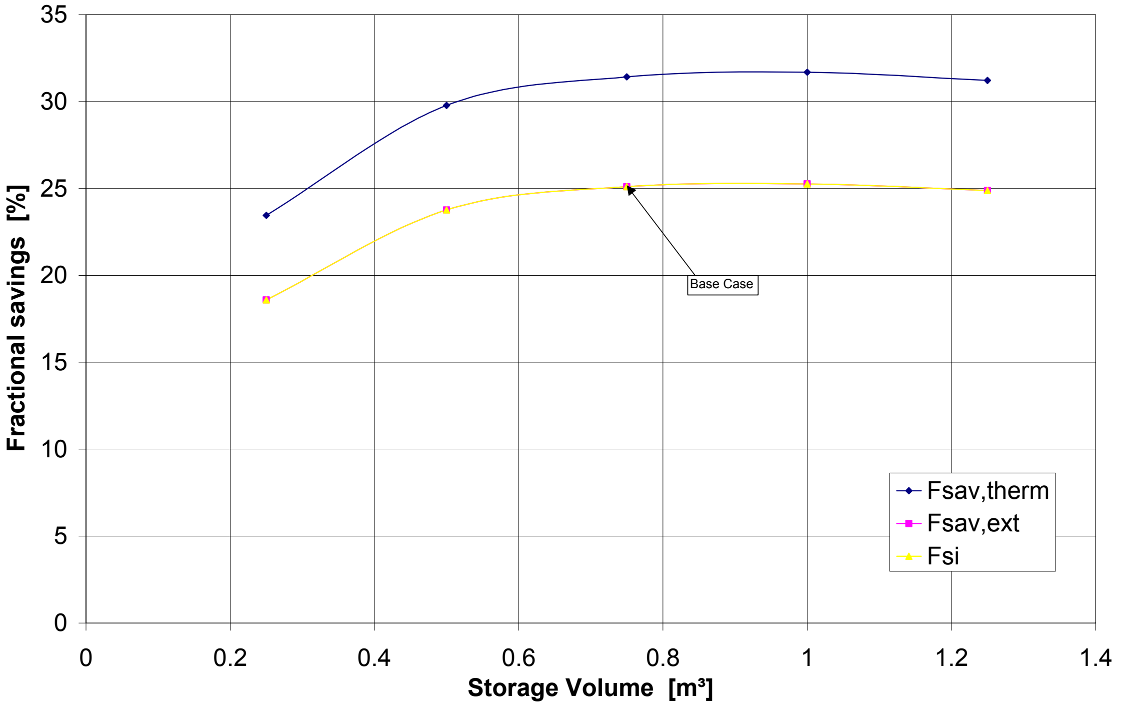


Figure 5. Variation of fractional energy savings with store volume with fixed collector area of 15 [m^2].

Differences from Base Case

- The height for the outlet of the auxiliary heat exchanger was varied so that the volume heated by the auxiliary was always the same (0.15 m^3).
- The height of the store is calculated with the following equation: H=Max[Min{2.2,1.78+0.39·ln(V)},0.8] where H is the storage height [m] and V is the storage volume [m³].
- The heat loss coefficient for the store varied using equations for the area of the relevant section. In addition, a volume sensitive "imperfection" factor, C_{corr}, was used to multiply the theoretical values: C_{corr}=Max[1.1,(1.5-V/10)] where V is the storage volume [m³].
- The vertical thermal conductivity is varied by the following equation: $\lambda_{vertical}$=Max[0.7,(1.3-V/10)].

Description of Results

Here the savings show an optimum storage volume at around 0.75 – 1.0 m^3, which corresponds to 0.05-0.67 m³/m² collector. Below this value, the store is too small to utilise the solar energy in the best way, especially since the volume heated by the auxiliary is always the same. Above this value the heat losses from the store start to outweigh the gain in utilised solar heat and the overall savings decrease again.

Comments

None.

Sensitivity parameter:	Collector Azimuth [°] (fixed tilt of 45°)	-90° - 90°

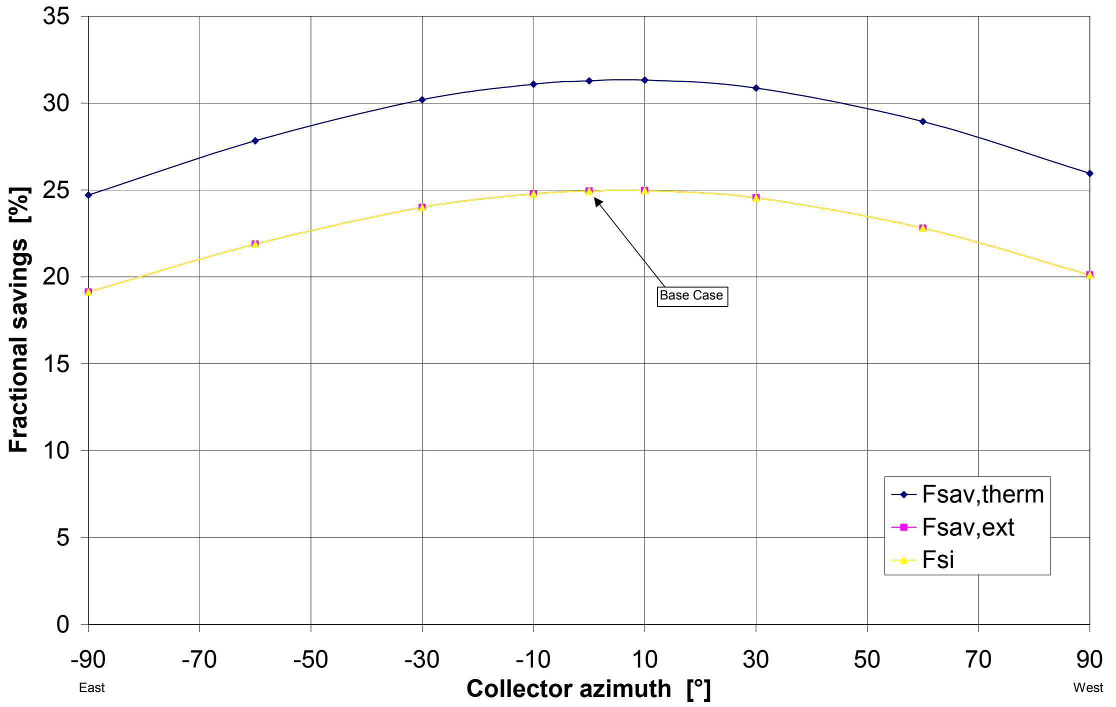


Figure 6. Variation of fractional energy savings with collector azimuth with fixed tilt angle of 45°.

Differences from Base Case
None

Description of Results
Here the savings show an optimum at around 10° west. Of course, this depends on the climate data and the consumption pattern (DHW and space heating). Generally, the ambient temperature is higher in the afternoon, which improves the collector performance. Therefore, for most climates and with an uniform consumption pattern during the day, a collector orientation slightly towards west is preferable.

Comments
None

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

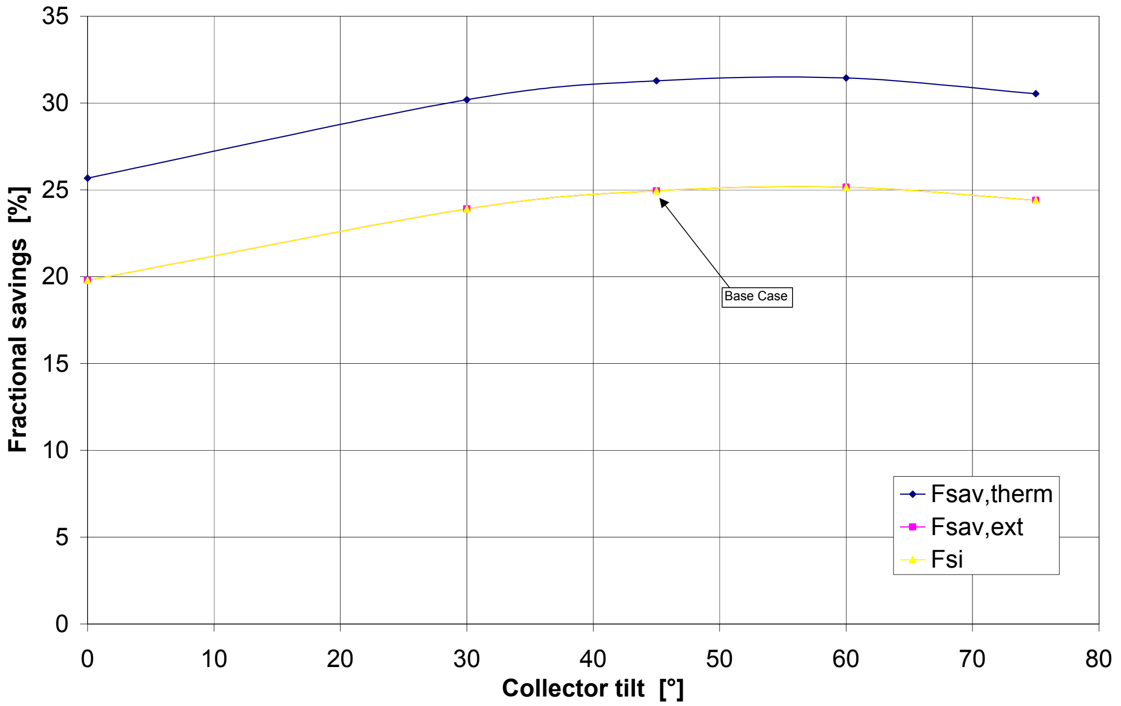


Figure 7. Variation of fractional energy savings with collector tilt, with fixed azimuth angle of 0°.

Differences from Base Case
None

Description of Results
Here the savings show an optimum at around 55° collector tilt. This is dependent on the location, climate and consumption pattern. Generally, the larger the space heating load in relation to the DHW load, the higher the optimum tilt angle.

Comments
The collector efficiency curve has not been changed due to the different tilts.

Sensitivity parameter:	Boiler Outlet Rel. Height [-]	0.5 – 0.9

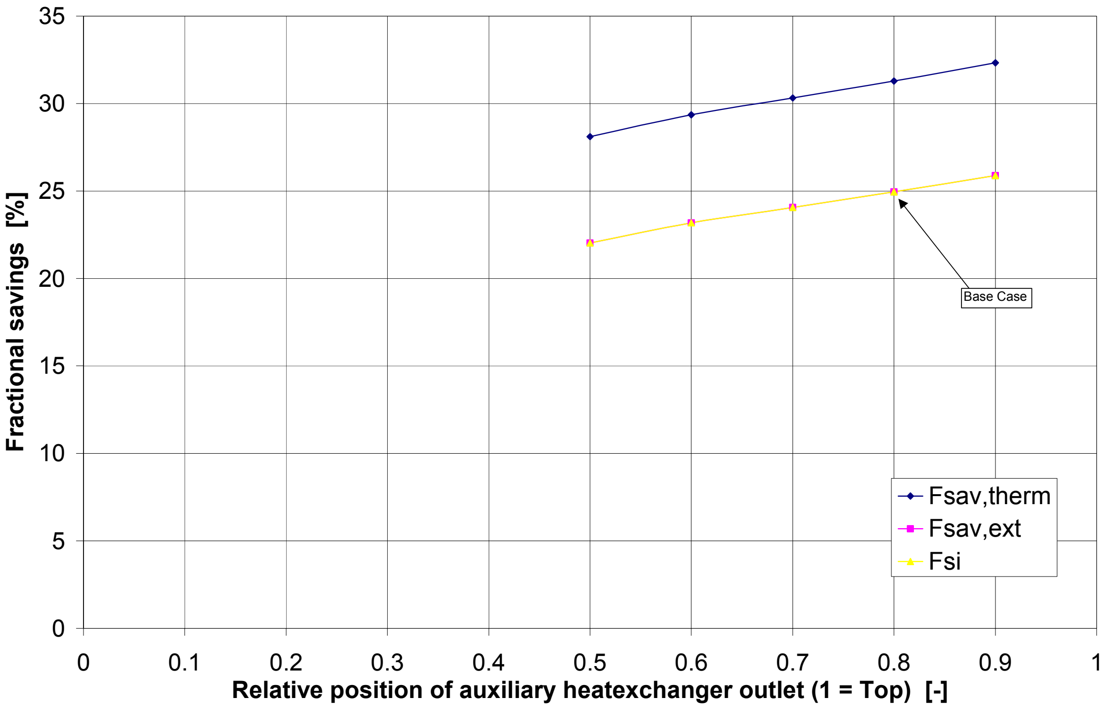


Figure 8. Variation of fractional energy savings with the auxiliary heat exchanger outlet.

Differences from Base Case
None

Description of Results
The savings increase with a smaller auxiliary volume. No penalties occurred for the settings (f_{si} = $f_{sav,ext}$) so even with an auxiliary volume of only 75 litres, the comfort is not decreased.

Comments
None

Sensitivity parameter:	Collector Heat Exchanger UA (variation from base case value)	-50% - +100%

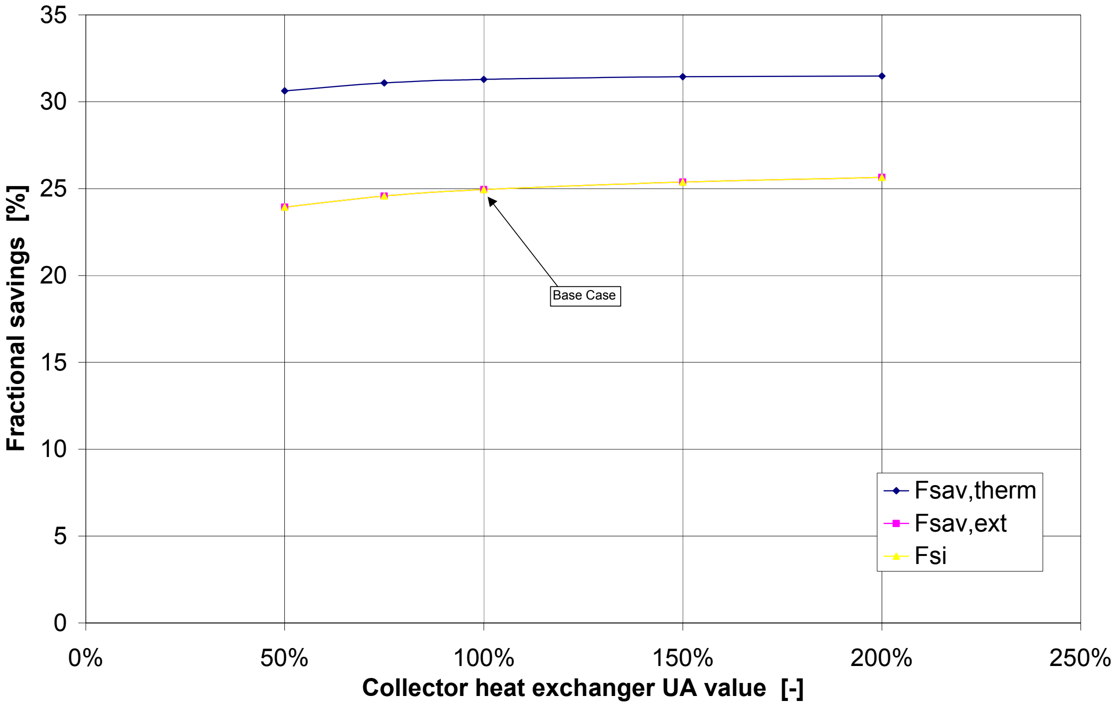


Figure 9. Variation of fractional energy savings with the UA-value of the collector heat exchanger. Parameter values are relative to the values defined for the base case system.

Differences from Base Case
None

Description of Results
Below the base case value (50 W/m² collector), the savings decrease increasingly rapidly. Above this value, there is only a marginal improvement in the savings.

Comments
None.

Sensitivity parameter:	Space heating Heat Exchanger UA (variation from base case value)	-50% - +100%

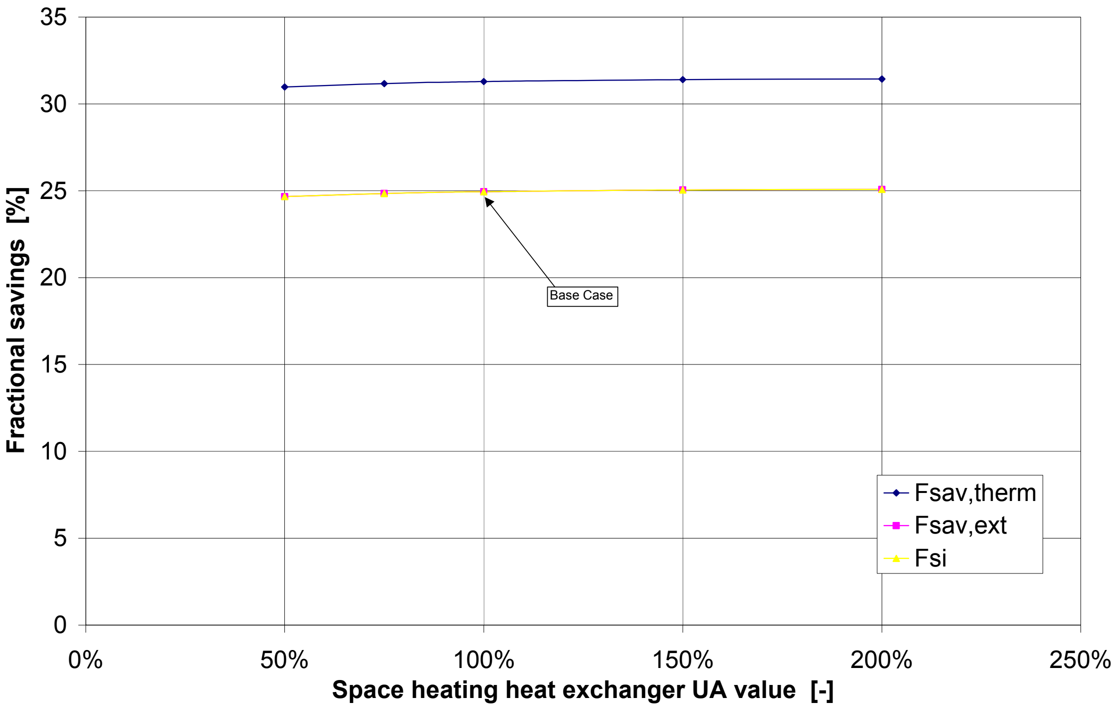


Figure 10. Variation of fractional energy savings with the UA-value of the space heating heat exchanger. Parameter values are relative to the base case UA-value.

Differences from Base Case
None

Description of Results
Within the investigated range, the UA-value has no influence on the savings.

Comments
None.

Sensitivity parameter:	Auxiliary Heat Exchanger UA (variation from base case value)	-50% - +100%

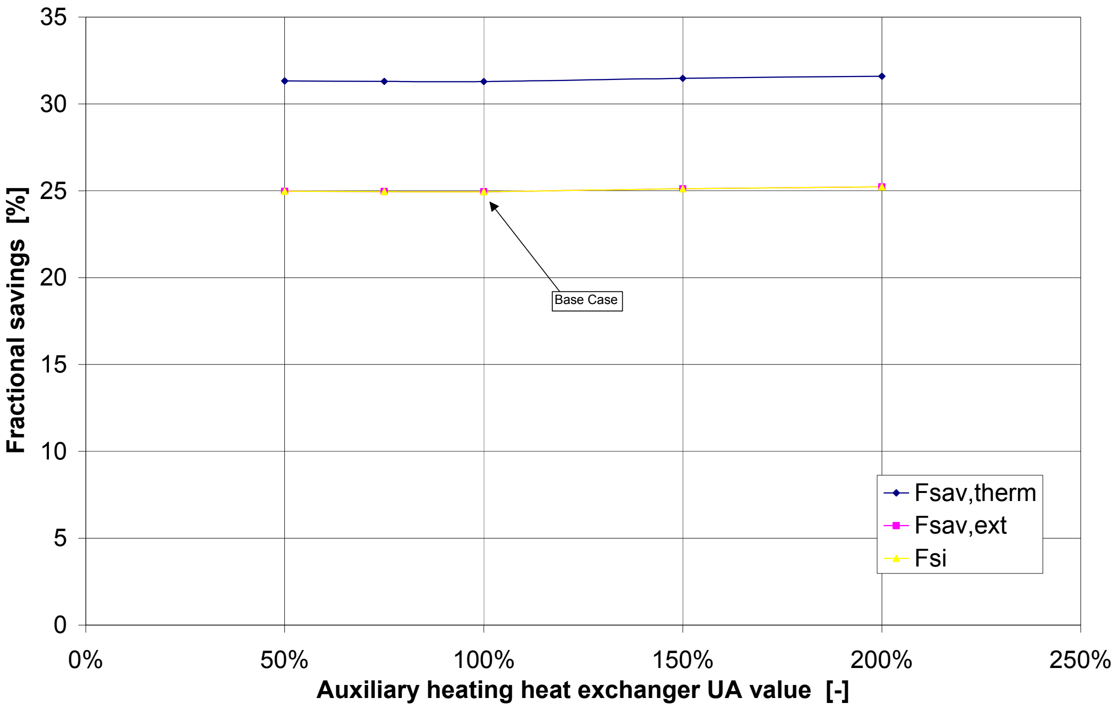


Figure 11. Variation of fractional energy savings with the UA-value of the auxiliary heat exchanger. Parameter values are relative to the base case UA-value.

Differences from Base Case
None

Description of Results
Within the investigated range, the UA-value has no influence on the savings.

Comments
None.

Sensitivity parameter:	Top insulation thickness	5 cm – 25 cm

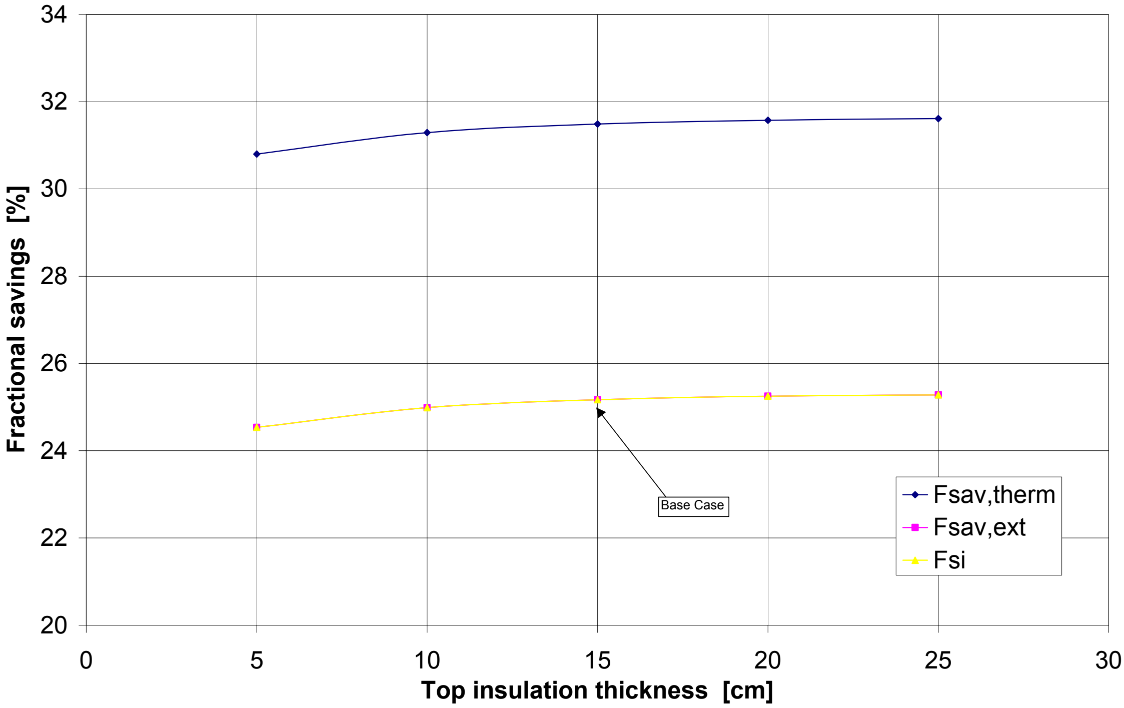


Figure 12. Variation of fractional energy savings with the top insulation thickness.

Differences from Base Case
None

Description of Results
For insulation thickness above the base case thickness of 15 cm, there is only a slight increase in savings. Below this thickness however, a decrease in the savings can be seen.

Comments
The insulation has a conductivity of 0.042 W/m-K and a correction factor for "imperfection" of C_{corr}=Max[1.1,(1.5-V/10)] where V is the storage volume [0.750 m³].

Sensitivity parameter:	Side insulation thickness	5 cm – 25 cm

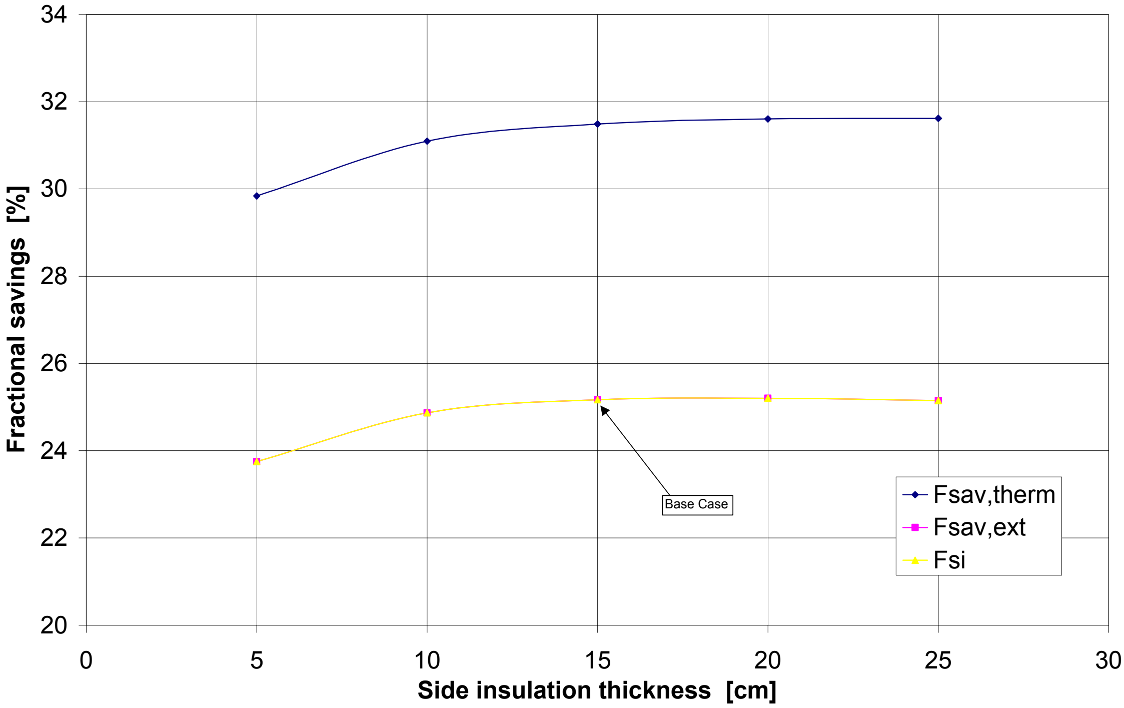


Figure 13. Variation of fractional energy savings with the side insulation thickness.

Differences from Base Case
None

Description of Results
For insulation thickness above the base case thickness of 15 cm, there is only a slight increase in savings. Below this thickness however, a decrease in the savings can be seen.

Comments
The insulation has a conductivity of 0.042 W/m-K and has a correction factor for "imperfection" of C_{corr}=Max[1.1,(1.5-V/10)] where V is the storage volume [0.750 m³].

Sensitivity parameter:	Bottom insulation thickness	0 cm – 25 cm

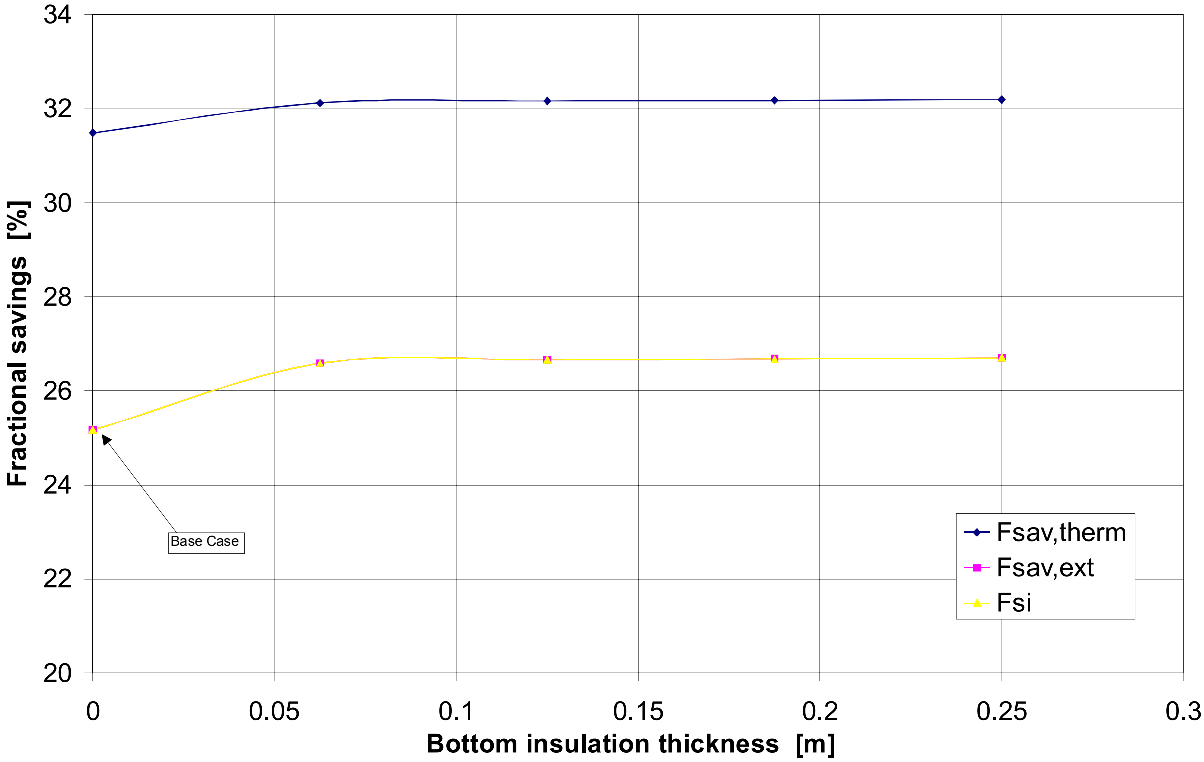


Figure 14. Variation of fractional energy savings with the bottom insulation thickness.

Differences from Base Case
None

Description of Results
For a bottom insulation thickness above approximately 5-6 cm, there is only a slight increase in savings. Below this thickness however, a decrease in the savings can be seen.

Comments
The insulation has a conductivity of 0.042 W/m-K and has a correction factor for "imperfection" of C_{corr}=Max[1.1,(1.5-V/10)] where V is the storage volume [0.750 m³].

Sensitivity parameter:	Store insulation thickness	5 cm – 25 cm

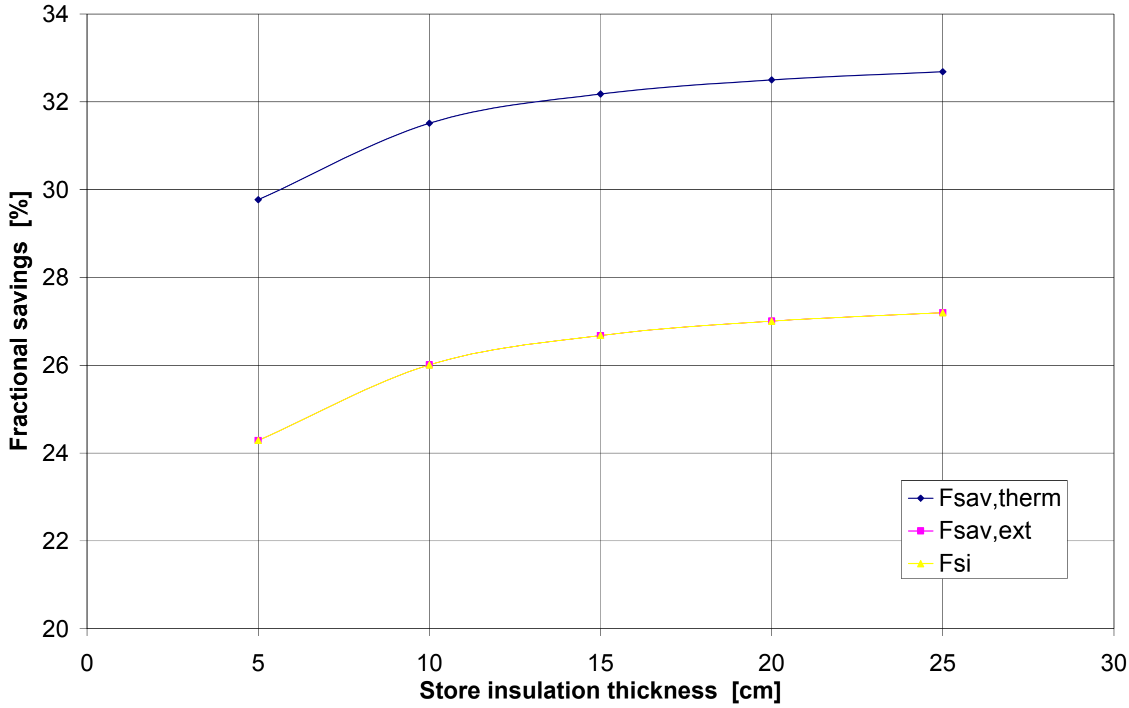


Figure 15. Variation of fractional energy savings with the store insulation thickness.

Differences from Base Case
None

Description of Results
In this case, the top-, the side- and the bottom insulation thickness are assumed equal. The figure shows that the savings increase with the thickness, however, for insulation thickness above 15 cm the increase in the savings is not so significant.

Comments
The insulation has a conductivity of 0.042 W/m-K and has a correction factor for “imperfection” of C_{corr}=Max[1.1,(1.5-V/10)] where V is the storage volume [0.750 m³].

Sensitivity parameter:	Collector Controller dT_{start} [K] (dTstop = 2 K)	2 K – 30 K

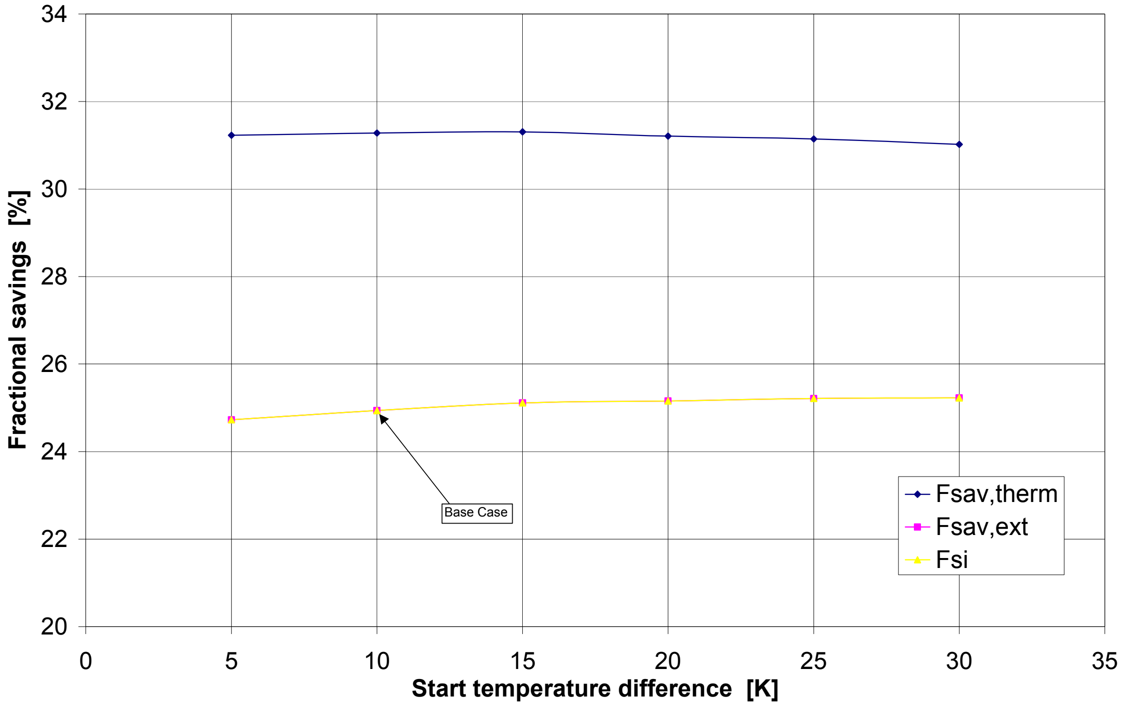


Figure 16. Variation of fractional energy savings with collector control start temperature difference.

Differences from Base Case
None

Description of Results
The thermal fractional saving has an optimum at a start temperature difference of around 15 K, however the extended fractional savings, which include the parasitic energy, has an optimum for a start difference of about 25 K. This means that the decrease in the thermal performance for start differences between 10 K and 25 K is outbalanced by the reduced electrical consumption of the collector loop pump.

Comments
None

Sensitivity parameter:	DHW set temperature [°C]	40°C – 60°C

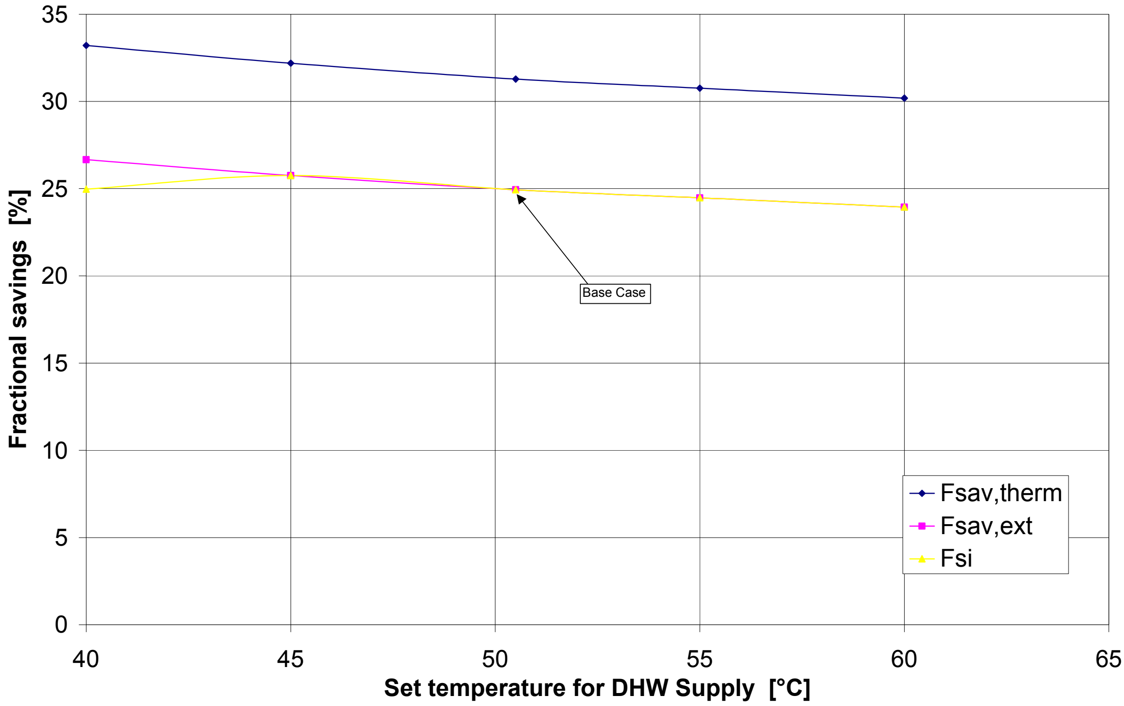


Figure 17. Variation of fractional energy savings set temperature for DHW supply.

Differences from Base Case
None

Description of Results
The fractional savings are influenced by the set temperature for the domestic hot water. The graph shows that for lower set temperatures, higher thermal and the extended fractional savings can be achieved. It can also be seen, that for set temperatures below 45°C the fractional savings indicator decreases, which means that the comfort level is not reached.

Comments
None

Sensitivity parameter:	Collector Control Sensor Rel. Height [-]	0.02 – 0.3

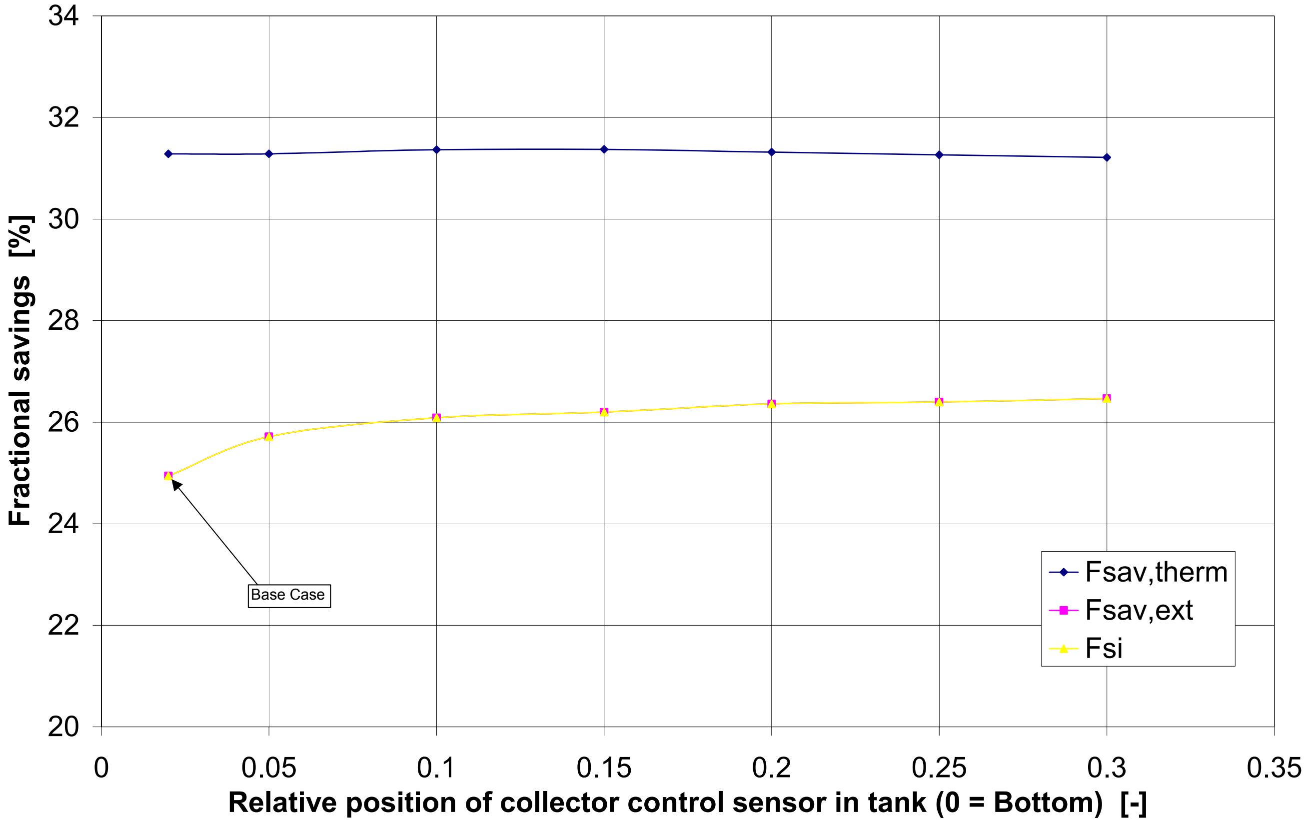


Figure 18. Variation of fractional energy savings with the position of the store sensor for the collector control.

Differences from Base Case
None

Description of Results
From the figure it appears, that the collector control sensor should be placed at least 10 % up in the tank. The solar heat exchanger is placed in the lower 1/3 of the tank and this means that the collector control sensor should be placed approximately in “the middle” of the heat exchanger.

Comments
None

Sensitivity parameter:	Space heating Controller Sensor Rel. Height [-]	0.4-0.7

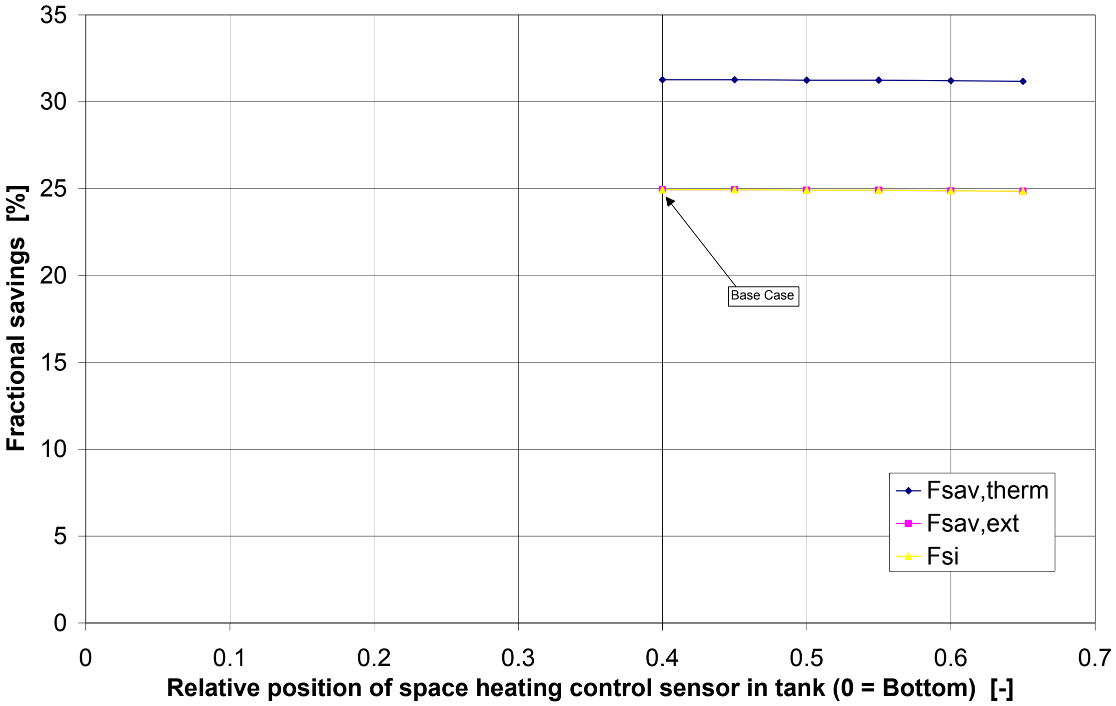


Figure 19. Variation of fractional energy savings with the position of the space heating control sensor.

Differences from Base Case
None

Description of Results
Within the investigated range, the position of the space heating control sensor has no influence on the savings.

Comments
None

Sensitivity parameter:	Climate (60 kWh SFH – Base Case)	Carpentras/Zurich/ Stockholm

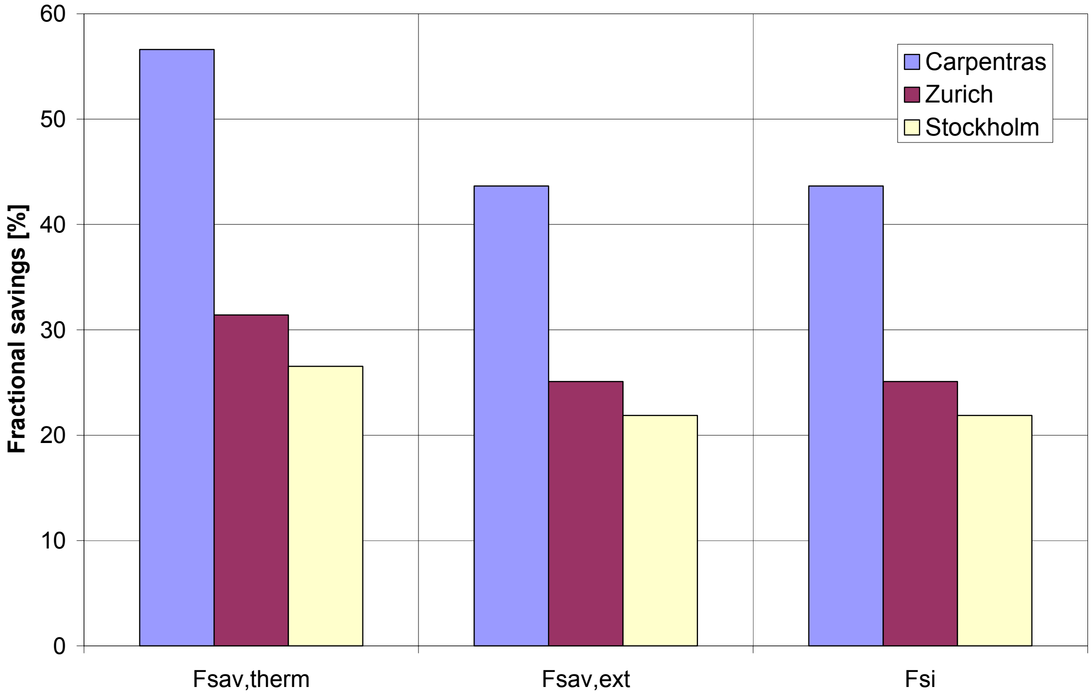


Figure 20. Variation of fractional energy savings for different climates.

Differences from Base Case
None

Description of Results
The results show that fractional savings for the Carpentras climate is much higher than for Stockholm and Zurich. Results for Stockholm and Zurich are quite similar despite the large geographic separation in latitude.

Comments
None

4.1.2 FSC results

In order to compare fractional savings for different climate and loads the following parameter, called **Fractional Solar Consumption (FSC)** is defined. It represents the proportion of energy consumptions for space heating and DHW which are “in phase” with available solar energy.

$$FSC = \frac{\sum_{1}^{12} \left(E_{ref.mont}, A \cdot H \right)}{\sum_{1}^{12} E_{ref,month}}$$

where

$E_{ref,month}$ is the monthly reference consumption without solar combisystem (kWh).

A is the solar collector area (m²)

H is the monthly global irradiation in the collector plane (kWh/m²)

Figure 21 illustrates the definition of FSC : $FSC =$ and in [6], full details about the method are given.

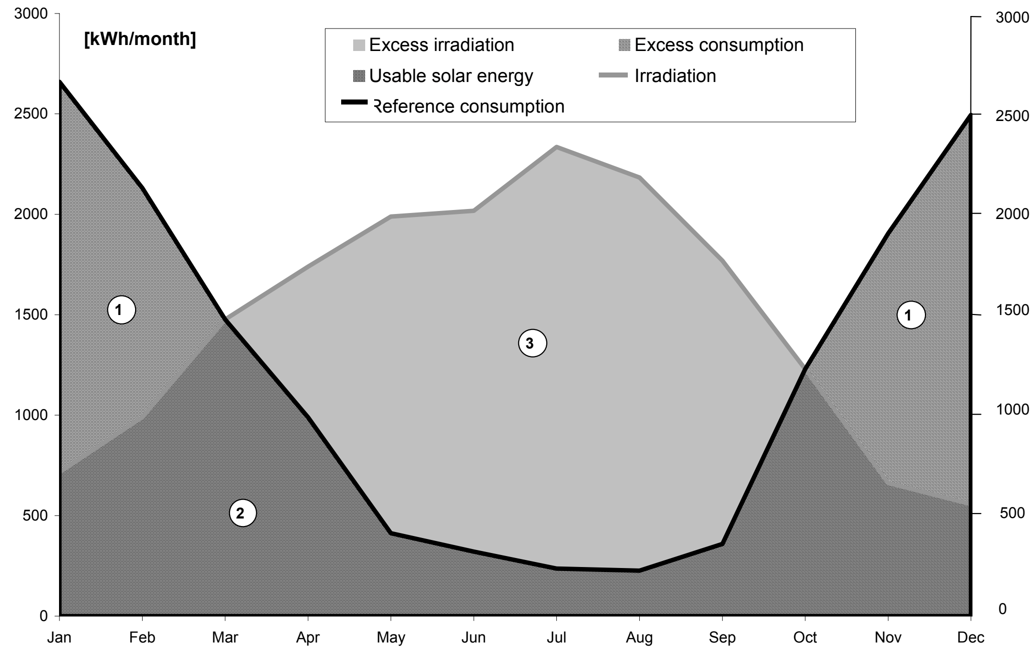


*Figure 21: D*efinition of the fractional solar consumption FSC

Figure 22 shows the fractional savings for the base case combisystem for:

- 3 climates: Stockholm, Zurich and Carpentras
- 3 collector areas: 5 m², 15 m ² and 25 m ²
- 3 space heating loads: SFH 30 kWh/m², SFH 60 kWh/m² and SFH 100 kWh/m²
- 1 domestic hot water load: 200 l/day

As an example, the figure shows that for a FSC value of 0.6 the thermal fractional saving is around 33% whereas the extended fractional saving is around 25%.

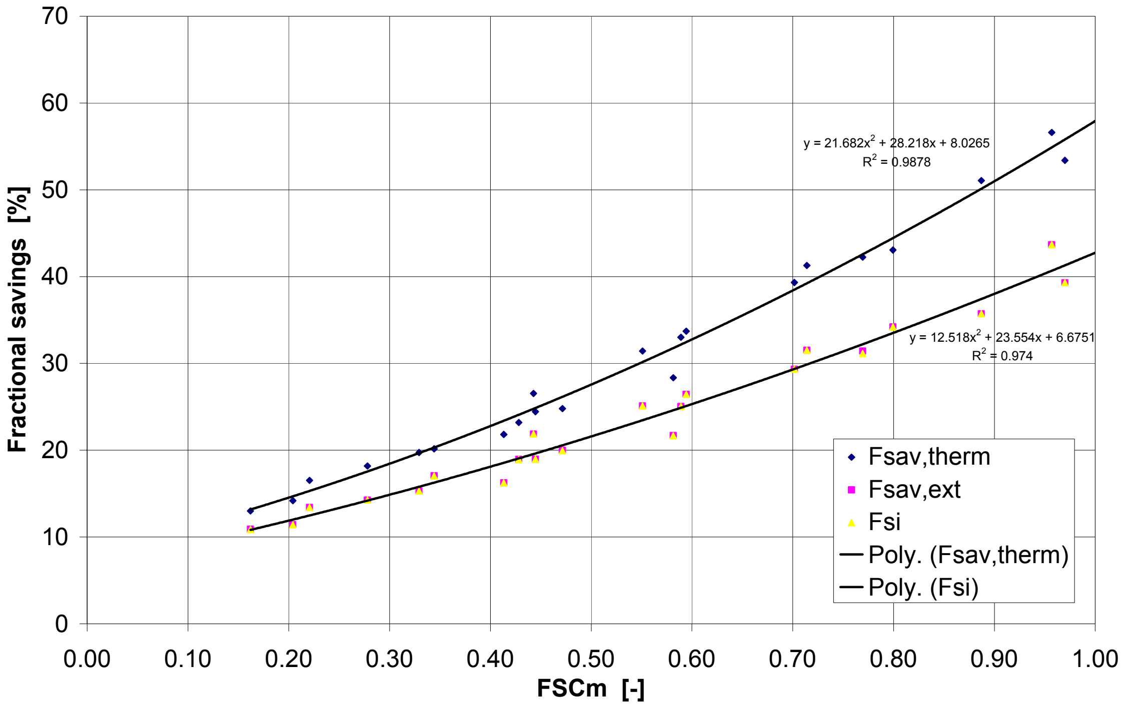


Figure 22: Fractional savings for the base case combisystem as a function of the FSC-value for 3 climates (Carpentras, Zurich, Stockholm) and 3 loads (30, 60, 100 kWh/m²a single family buildings).

4.2 Definition of the improved system

Based on the sensitivity analysis, a suggestion for an improved system is made. The major differences from the base case systems are that:

- The auxiliary volume is reduced to 0.075m³
- An electrical heating element is used in the storage tank during summertime
- The bottom of the storage is better insulated (5 cm of insulation)
- There are no thermal bridges (no correction for insulation imperfection)
- The storage temperature sensor for the collector control is moved up to the level of the collector heat exchanger inlet.
- The auxiliary set temperature is reduced to 45°C

4.2.1 FSC results for the improved system

Figure 23 shows the fractional savings for the base case combisystem for:

- 3 climates: Stockholm, Zurich and Carpentras
- 3 collector areas: 5 m², 15 m ² and 25 m ²
- 3 space heating loads: SFH 30 kWh/m², SFH 60 kWh/m² and SFH 100 kWh/m²
- 1 domestic hot water load: 200 l/day

Now, the figure shows that for a FSC value of 0.6 the thermal fractional saving is around 38% whereas the extended fractional saving is around 34%.

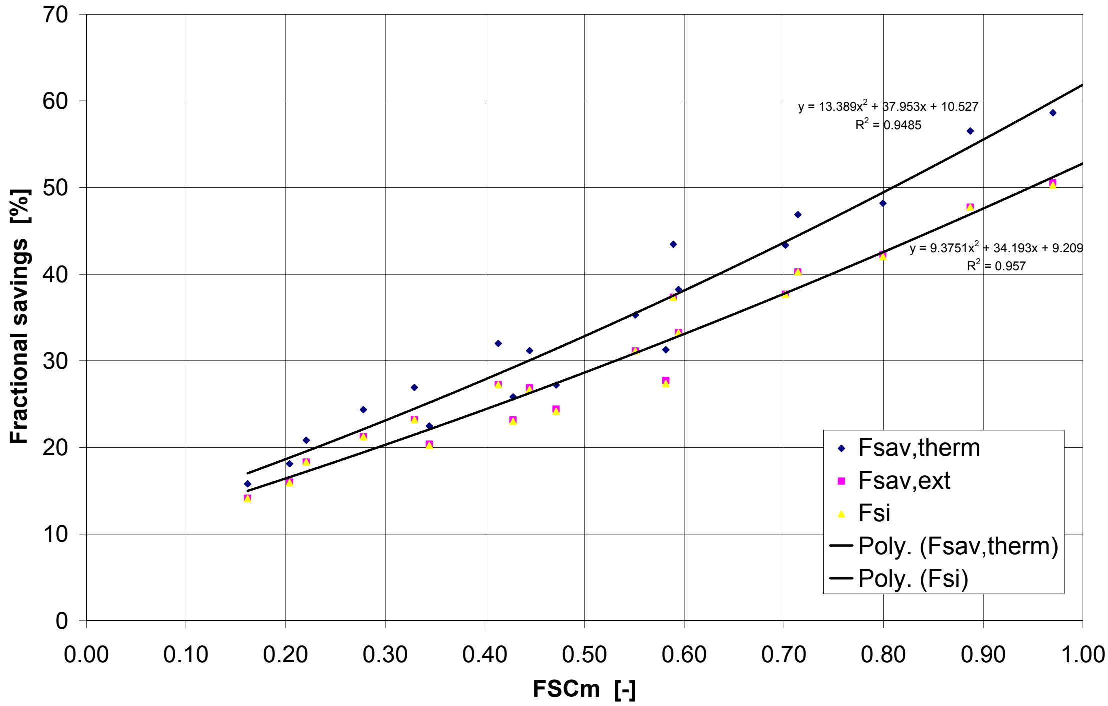


Figure 23: Fractional savings for the improved combisystem as a function of the FSC-value for 3 climates (Carpentras, Zurich, Stockholm) and 3 loads (30, 60, 100 kWh/m²a single family buildings), Improved system.

5 Conclusion

A Danish solar combisystem is theoretically investigated in this report.

The principle of the system is that it is a standard solar domestic hot water system, in which the collector area has been oversized, in order to be able to deliver energy to an existing space heating system. This is made through an extra heat exchanger included in the DHW tank.

A TRNSYS model of the system is developed and a sensitivity analysis is performed by means of TRNSYS simulation. This analysis showed that the system could be improved by:

- Reducing the auxiliary volume
- Using an electrical heating element in the storage tank during summertime
- Insulating the bottom of the storage better
- Eliminating all thermal bridges in the storage tank insulation
- Moving up the storage temperature sensor for the collector control to the level of the collector heat exchanger inlet.
- Reducing the auxiliary set temperature to 45°C

By improving the system, the thermal fractional saving can be increased about 5%pts.

6 References

[1]	Klein S.A et al. (1996):	TRNSYS 14.2, User Manual. University of Wisconsin Solar Energy Laboratory.
[2]	Drück, H. & Pauschinger, T. (1997)	Multiport Store – Model for TRNSYS Type 140 version 1.90, Institut für Thermodynamik und Wärmetechnik, Universität Stuttgart.
[3]	Bales, Chris	TRNSYS Type 170 Gas/Oil/Biomass.boiler module. Version 3.00. Högskolan Dalarna, Solar Energy Research Center – SERC, EKOS. S-78188 Borlänge
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[5]	Streicher, Wolfgang	Structure of the reference buildings of Task 26, Technical report, IEA SHC Task 26 Solar Combisystems, http://www.iea-shc.org, 2003.
[6]	Letz, Thomas	Validation and background information on the FSC procedure, IEA SHC Task 26 Solar Combisystems, http://www.iea-shc.org, 2003.