Report on Solar Combisystems Modelled in Task 26

Appendix 6: Generic System #11: Space Heating Store with DHW Load Side Heat Exchanger(s) and External Auxiliary Boiler

A Report of IEA SHC - Task 26

Solar Combisystems

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INTERNATIONAL ENERGY AGENCY
Solar Heating & Cooling Programme

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Appendix 6: Generic System #11: Space Heating Store with DHW Load Side Heat Exchanger(s) and External Auxiliary Boiler

by

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A technical report of Subtask C

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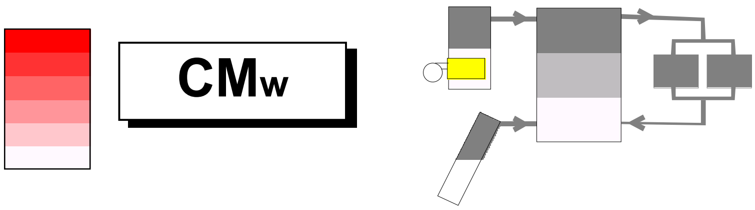
Contents

1 General description of System #11 Space Heating Store with DHW Load-Side Heat Exchanger(s) and External Auxiliary Boiler

Sweden (Finland)

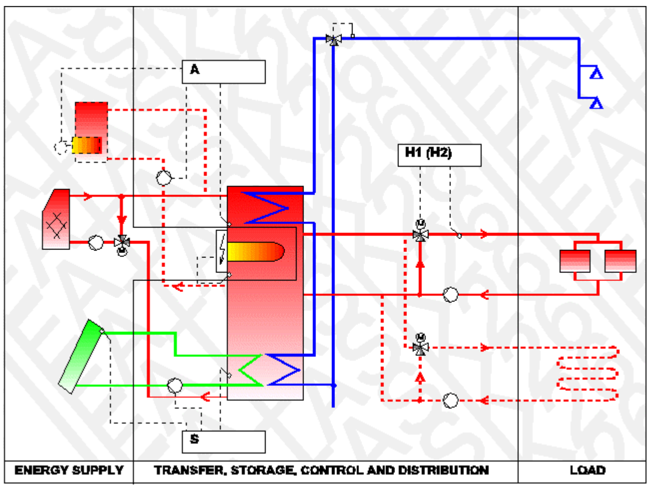


Main features

The tank in this system is fitted with an immersed horizontal finned-coil heat exchanger for DHW preparation and another heat exchanger in the bottom for the collector loop. An electric heater, operating on demand, heats the upper third of the tank. The optional use of a wood boiler or a pellet burner is very common in these systems. In Sweden an optional heat exchanger is generally used for DHW preheating as this significantly improves the thermal performance of the system. In Finland, this system is usually designed with a smaller collector area and a smaller storage tank (750 l) than in Sweden.

Heat management philosophy

The pump of the collector loop is under control of a simple differential controller. The pump is switched off when the temperature at the collector outlet reaches 95°C. No control for space heating and auxiliary boiler is included in the system. The electric heater is under control of a separate thermostat.



Specific aspects

Overheating is prevented by using a relatively small expansion vessel (10 - 30% of collector loop volume), and by allowing a high pressure of up to 6 or 9 bar. This ensures that the fluid in the collector does not boil. Due to the way DHW is prepared, there are no legionella risk.

Influence of auxiliary energy source on system design and dimensioning

Depending on the type of auxiliary boiler used, the outlet connection is located at the bottom of the tank (wood logs boiler) or in the middle of it (pellet burner). In the first case, the whole tank is heated up when the boiler is used. In the second case, only the upper part is heated up. One or more buffer tanks can be added in conjunction with a wood boiler. In this way, the boiler's requirement for a large volume is satisfied and the collector loop can still use a part of the whole volume by manually or automatically connecting or disconnecting the buffer tanks. An electric auxiliary heater is always included in the tank.

Cost (range)
Sweden: A typical system with 10 m² of solar collectors and a 1 500 litre storage with a wood boiler as auxiliary, costs about 12 300 EUR. A similar reference system without solar heating costs about 8 600 EUR.

Finland: A typical system with 7 m² of solar collectors and a 700 litre storage without boiler (all auxiliary energy with electricity) costs about 9 100 EUR. A similar reference system without solar heating costs about 6 100 EUR.

Market distribution
This system has been marketed in Sweden since 1990. About 5 companies have installed 10 000 to 20 000 m² of solar collectors. In Finland this system is quite new. About 80 systems, with 800 m² of solar collectors have been installed, from Helsinki to beyond the Arctic Circle.

Manufacturers in Sweden: Three or four companies are manufacturing these storage tanks and about the same number of manufacturers produce the collectors. Marketing is by several companies. It is the preferred system among selfbuilders in Sweden involving some 20 small companies. (BoRö pannan AB - industry participant, manufactures and sells the system).

Manufacturers in Finland: Two companies are manufacturing and four companies are selling these systems in Finland. (FORTUM - industry participant, manufactures and sells the system).

2 Modelling of the system

2.1 TRNSYS model

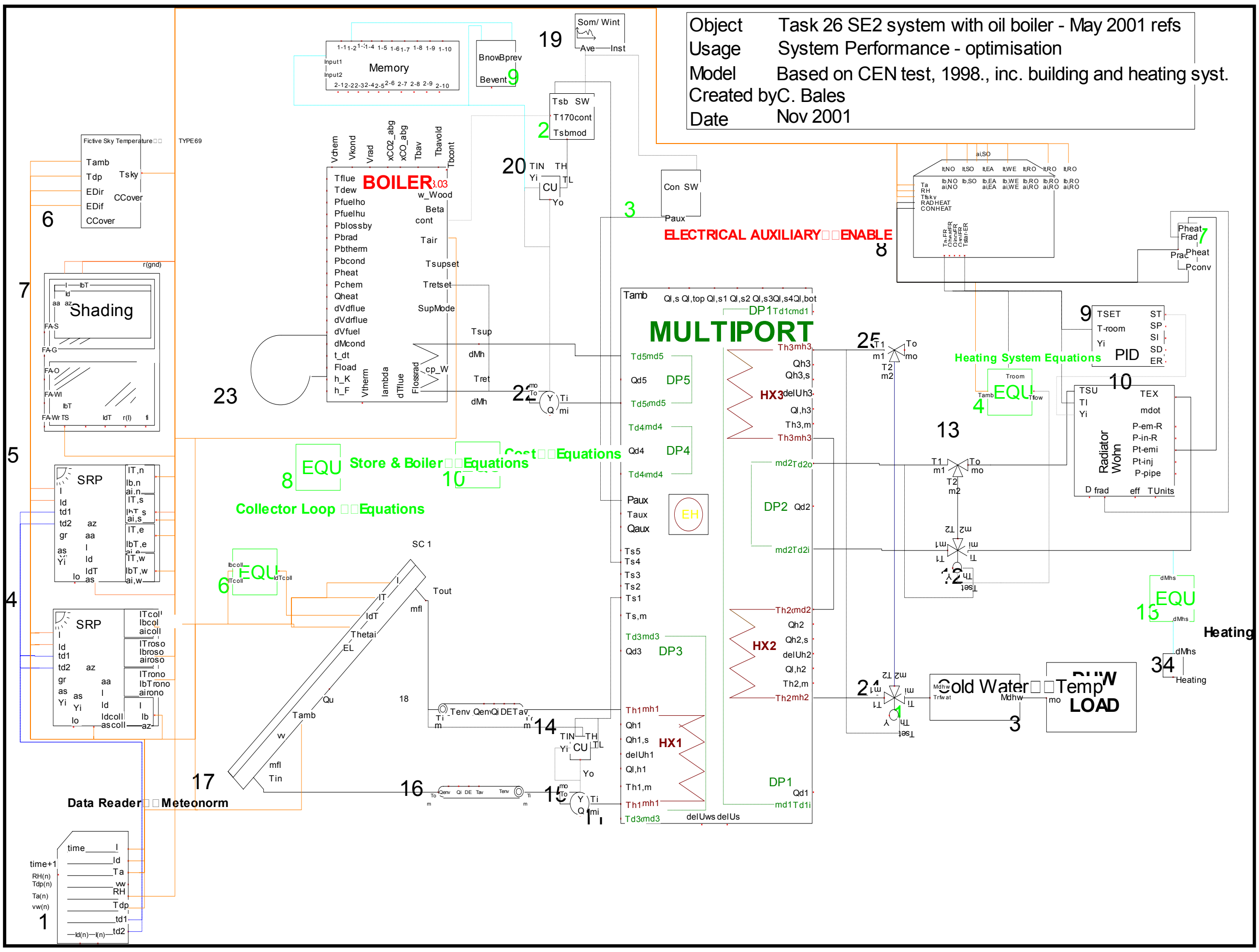


Fig. 1. Modelling of System #11 in PRESIM/TRNSYS. The black numbers are the unit numbers and the green ones the order of the equations sets.

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

The definitions below show what values have been used in the base case and how they have been derived. The figures in brackets after the component type refer to the component number in Fig. 1.

2.3 Collector

Type 132 (17)	η0, a1, a2, inc. angle modifier (50°)	0.8, 3.5, 0.015, 0.9
	Area	10 m²
	Specific mass flow	50 l/m²h

Data defined in (Weiss, 2003)

2.3.1 Pipes between Collector and Storage:

Type 31 (16 & 18)	Inner diameter	0.01 m
	Insulation thickness	0.02 m
	Length	2 x 15 m
	Thermal conductivity (theoretical value used)	0.04 W/m.K

Data values defined in (Weiss, 2003)

2.3.2 Store:

Type 140 v1.95 (11). The majority of parameter values used here were those identified using prEN12977-3 in May 1999. The ones that differ are the heat loss coefficients. Different manufacturers use different versions of the store with slightly varying heights and sizes of heat exchangers as well as insulation quality. The test results are shown in Appendix B and include the verification results. The heat loss values used here are as below. They are similar in size for loss coefficients identified for stores of the same size.

Heat Losses

UA-value for sides [W/K] = (0.04/dinmzo)*UAlscorr*2*$(Vs*Hs*\pi)^{0.5}$ = 2.45 [W/K]
UA-value for top [W/K]= (0.04/dinmto)*UAlscorr*(Vs/Hs) = 0.30 [W/K]
UA-value for bottom [W/K] = (0.04/dinmbo)*UAlscorr*(Vs/Hs) = 0.30 [W/K]
Where:

UAlscorr = Correction term: UA-value/theor. UA = MAX(1.3, (2.0-Vs/10)) (= 1.93)
Vs = store volume (0.729) [m^3]
Hs = store height (1.58) [m]
dinmzo = insulation thickness for sides (0.12) [m]
dinmto = insulation thickness for top (0.12) [m]
dinmbo = insulation thickness for bottom (0.12) [m]

Auxiliary Heated Volume

Instead of heights in the store, the useful volume heated by the boiler and electrical heater has been used as an input parameter. This volume is defined as the volume between the upper point of the DHW heat exchanger and the outlet to the boiler. This outlet is at the same height as the electrical heater mounted in the store. The upper DHW heat exchanger is placed at a higher height than identified for the store, 0.95 instead of 0.879 in order to have less dead volume.

Height for outlet of upper DHW heat exchanger 0.950
Height for boiler outlet/electrical auxiliary (zobo) = 1 – (AuxVol/Vs) – 0.05 = 0.607

Where:

AuxVol is the auxiliary heated volume (0.25 m^3)

Positions of Sensors for Controllers

The heights for the temperature sensors were not identified. In practice, different manufacturers have them at different heights. These were set to the following (heights are relative heights with 1 for the top, 0 for the bottom):

Height for collector controller 0.100
Height for boiler controller = zobo + 0.06 = 0.667
Height for electrical heater thermostat= zobo + 0.02 = 0.627

2.3.3 Boiler (Auxiliary Heating)

Type 170 (23) – Specific Type, data defined by Bales (in agreement with Task 26) for standard oil boiler. The burner is controlled using an external on/off controller (20) and uses a shunt to give more realistic properties for the boiler. Version 3.03 of this type was used.

Aux. Boiler	Heating capacity (SFH)	15 kW
	Mean efficiency (Zurich, 60 kWh/m^2.yr)	80 %
	Control mode	10
	Mass of water in burner	37 kg
	Air surplus factor	1.12
	$\Delta\vartheta$ between exhaust gas and incoming water	100 K
	Reference temperature for loss calculation (param 6)	62°C
	Radiation losses at max. heating rate	4.9%
	Standby losses (% of max heating rate)	0.7%
	Standby temperature for burner	75°C
	Start $\Delta\vartheta$, hysteresis, auxiliary internal	5 K
	Flow rate for charging store	600 kg/h

2.3.4 Building

Type56, (Streicher, 2003)

2.3.5 Heat distribution

Type 162 (Weiss, 2003)

2.3.6 Control strategy

(Udb .. Upper dead band; Ldb .. Lower dead band)

Controller 1 : Type 2
Functions : Collector Controller
Udb=8 K Ldb=1 K
Tupi= $T_{CollectorOut}$ Tloi= $T_{store(0.10)}$

Controller 2 : Type 120
Functions : PID Controller / Radiator
Width of PID-band ± 3 K
Proportional gain 0.8
Integral gain 0.05
Differential gain 0.0

Controller 3 : Type 2 as simple on/off controller
Functions : Store Charge Controller
Udb=8 K Ldb=0 K
Turn off (upper) temperature=70°C
Tupi= $T_{store(0.667)}$

2.4 Validation of the System Model

The system has not been validated as a whole system. The store including electrical heater and heat exchangers for solar and hot water has been validated. See parameter identification report at the end of this report, section 2.8.

3 Simulations for testing the library and the accuracy

3.1 Result of the TRNLIB.DLL check

The following are the results for the SCS1a.trd file of Feb. 2001. One major difference in the DLL used for system #11 is that a later version of the boiler model type 170 was used. This included some bug fixes as well as some changes to the operation as oil boiler.

#19, scsth	$F_{sav,therm}$	$F_{sav,ext}$	F_{SI}	E_{boiler}	$Q_{penalty,SH,Low}$	$Q_{penalty\,SH,Up}$	$Q_{penalty\,DHW}$	Q_{sol} [MWh]	Q_{coll} [MWh]
Graz DLL	0.7900	0.7406	0.3006	9443	30	26480	0	604.2	96.7
SERCs DLL	0.782	0.733	0.292	9815	31	26510	0	603.5	95.8
Difference(rel.)	-1.5%	-1.5%	-0.2%	5.7%	2.9%	-1.9%	0.00 %	0.1%	0.9%

#11, cost optimised, gas	$F_{sav,therm}$	$F_{sav,ext}$	F_{SI}	E_{boiler}	$Q_{penalty,SH,Low}$	$Q_{penalty\,SH,Up}$	$Q_{penalty\,DHW}$	Q_{sol} [MWh]	Q_{coll} [MWh]
Graz DLL	29.7%	25.0%	25.2%	10110	0	6207	50	11740	3227
SERCs DLL	29.7%	25.0%	24.8%	10100	0	6299	29	11780	3232
Difference(rel.)	0.2%	0.2%	-1.6%	-0.1%	0.0%	1.5%	-41%	0.3%	0.2%

3.2 Results of the accuracy and the time step check

Results for the system used for the sensitivity analysis based on the reference conditions from 2000. The procedure for choosing the conditions was as follows:

- Simulate the system for the tightest tolerance (0.001), shortest time step (1/64) and 100 store nodes. This is defined as the reference simulation.
- Simulate for a variety of different tolerances, time steps and store nodes.
- Choose the one with the fastest simulation time that has an epsilon value (relative difference to reference simulation) of less than 1%.

The lighter grey row is the reference for the comparison, and the darker grey the chosen values for the sensitivity analysis. The other sets with low epsilon values were not chosen as they had substantially higher epsilon values for F_{si}.

Thus convergence tolerance of 0.001, time step of 1/32 and 100 store nodes was chosen.

Converg. = Integ. Tolerance	**Nodes in Store**	**Time Step**	$\mathbf{F_{sav,therm}}$	**Epsilon**
0.010	100	1/20	14.81%	-5.2%
0.005	100	1/20	15.56%	-0.4%
0.001	100	1/20	15.60%	-0.1%
0.010	100	1/64	15.05%	-3.6%
0.005	100	1/64	15.40%	-1.4%
0.001	100	1/64	15.62%	0.0%
0.010	100	1/32	15.36%	-1.7%
0.001	100	1/32	15.61%	-0.1%
0.001	40	1/32	14.63%	-6.3%
0.001	20	1/32	14.29%	-8.5%

The values for the optimisation process were different to those for the sensitivity analysis as the reference conditions had changed slightly as well as certain bugs had been fixed. These new simulations were based on the reference conditions from May 2001. The same procedure was used as for the sensitivity analysis. The lighter grey row is the reference simulation for the comparison, and the darker grey the chosen values for the optimisation. A slightly higher value of epsilon was allowed as it was necessary to have a short run time for the simulations as the optimisation was performed using an automatic optimisation tool and many simulation runs were required.

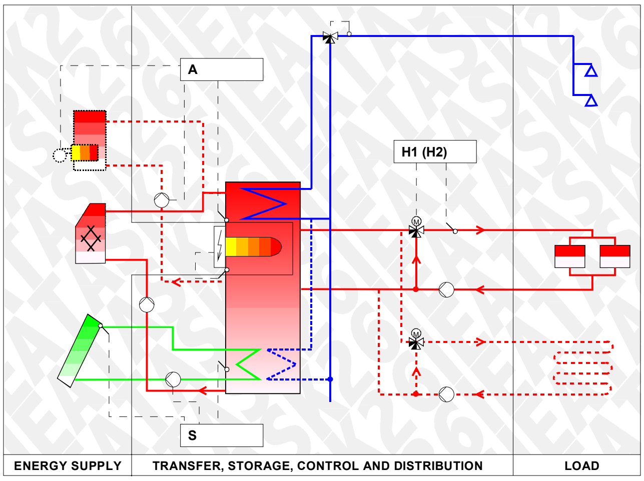
Thus convergence tolerance of 0.001, time step of 1/20 and 100 store nodes was chosen.

Converg. = Integ. Tolerance	**Nodes in Store**	**Time Step**	**$F_{SAV,therm}$**	**Epsilon**
0.010	100	1/20	13.85%	-3.8%
0.005	100	1/20	13.90%	-3.5%
0.001	100	1/20	14.17%	-1.6%
0.010	100	1/40	14.28%	-0.8%
0.005	100	1/40	14.27%	-0.9%
0.001	100	1/40	14.40%	0.0%
0.001	40	1/40	14.15%	-1.7%
0.001	40	1/40	14.15%	-1.7%
0.001	20	1/40	13.87%	-3.7%
0.001	20	1/40	13.87%	-3.7%

4 Sensitivity Analysis and Optimisation

4.1 Sensitivity Analysis of Base Case

This sensitivity analysis was performed at the end of 2000 and thus included the reference conditions that were valid at that point of time. These were not the final reference conditions. However, the trends shown here would not be affected by these small changes.



#11 Space Heating Store with DHW Load Side Heat Exchanger(s) and External Auxiliary Boiler (Finland, Sweden)

Main parameters (Base Case) : Store parameter values, except for insulation, derived using prEN 12977-3.			
Building :	*SFH 60*	Storage Volume :	*0.73 m³*
Climate :	*Zurich*	Storage height	*1.6 m*
Collectors area :	*10 m²*	Position of heat exchangers	*typical*
Collector type :	*Standard Flat Plate*	Position of in/outlets	*typical*
Specific flow rate (Collector)	*50 kg/m²h*	Thermal insulation, store (top, bottom & sides)	*12 cm*
Collector azimuth/tilt angle	*0 / 60°*	nominal aux. heating rate: Oil boiler Elect. heater in store	 *15 kW* *6 kW*
[1]Collector heat exchanger UA-value at typical operating conditions	*500 W/K*	[1]Lower DHW heat exch. UA-value at typical operating conditions	*950 W/K*
Collector tubing & insulation	*12 mm O/D* *20 mm*	[1]Upper DHW heat exch. UA-value at typical operating conditions	*1500 W/K*
Collector controller upper/lower dead band	*8/1 K*	Store charge controller & el. heater thermostat	*62°C - 70°C*
Store charge flow rate	*600 kg/h*	Oil boiler operating and standby temperature (upper)	*75°C*
Simulation parameters:		Storage nodes	*100*
Time step	*1/32 h*	Tolerances Integration Convergence	*0.001 / 0.001*

[1] The UA-value is that identified for the type 140 store model from measurements. The identified parameters include factors for flow and temperature dependency. The values given here are for typical operating conditions. Note that since the heat exchangers are immersed in the store fluid, and cover several nodes of the store, a slightly different definition of UA-value is used compared to that for counter-flow heat exchangers.

Summary of Sensitivity Parameters		
Parameter	**Variation**	**[1]Variation in $f_{sav,ext}$**
Base Case	**-**	**11.5%**
Collector size [m^2] (fixed store size (0.73 m^3)	5 – 30 m^2	3.3 – 23.0%
Collector Size [m2] (fixed store spec. vol. 0.075 m^3/m^2)	5 – 30 m^2	2.3 – 28.1%
Store Size [m3] (fixed collector area of 10 m^2)	0.3 – 3.0 m^3	3.2 – 12.2%
Collector Tilt [°] (fixed azimuth of 0°)	15° - 90°	2.9 – 12.2%
[2]Climate (60 kWh SFH)	Carp. / Zur. / Stock.	27.6% / 9.5% / 9.0%
[2]Building (Zurich Climate)	30 / 60 / 100	11.4% / 9.5% / 7.3%
Collector Heat Exchanger Outlet Rel. Height [-]	0.000 – 0.236	4.7 – 11.5%
Lower DHW Heat Exchanger Inlet Rel. Height [-]	0.100 – 0.500	0.7 – 11.9%
[3]Upper DHW Heat Exchanger Outlet Rel. Height [-]	0.850 – 1.000	11.3 – 11.6%
[3]Boiler Inlet Rel. Height [-]	0.749 – 0.999	11.5 – 11.6%
[3]Boiler Outlet & Electrical Heater Rel. Height [-]	0.407 – 0.807	7.7 – 13.6%
[3]Heating System Inlet Rel. Height [-]	0.000 – 0.500	11.3 – 11.5%
[3]Heating System Outlet Rel. Height [-]	0.715 – 1.000	11.4 – 11.6%
Collector Heat Exchanger UA (variation from identified value)	-50% - +100%	10.7 – 11.8%
[3]Lower DHW Heat Exch. UA (variation from identified value)	-50% - +100%	10.9 – 11.7%
[3]Upper DHW Heat Exch. UA (variation from identified value)	-50% - +100%	11.4 – 11.5%
[4]Store Insulation: top [cm]	4 – 18 cm	9.3 – 11.8%
[4]Store Insulation: sides [cm]	4 – 18 cm	-1.4 – 13.3%
[4]Store Insulation: bottom [cm]	4 – 18 cm	10.9 – 11.5%
[4]Store Insulation: whole store [cm]	4 – 18 cm	-4.5 – 13.7%
Store Insulation [-] (for stores measured in lab)	-	10.3 – 14.4%
Collector Controller dT_{start} [C] (constant dTstart/dTstop)	4 – 12	11.3 – 11.5%
[5]Boiler Internal Standby Temperature [C]	75 - 90°C	9.7 – 11.5%
[6]Store Charge/Electrical Heater Thermostat (off) [C]	60 - 80°C	8.1 –11.5%
Store Charge Flow Rate [kg/h]	400 –1200 kg/h	10.6 – 11.6%
Store Charge Controller Sensor Rel. Height [-]	0.627 – 0.787	10.7 – 11.6%
Collector Controller Sensor Rel. Height [-]	0.050 – 0.500	10.9 – 11.5%
[7]Tube Insulation Thickness [cm]	0.5 – 3.0 cm	11.3 – 11.5%
Auxiliary Heater Type (Stockholm climate, 60 kWh/m2.yr house)	-	-70.6 – 18.1%
Period for Boiler Shutdown / El. Heating (Stockholm climate, 60 kWh/m2.yr house)	0 - 365	-70.6 – 10.6%

[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.

[2] These were simulated with oil boiler on all year, resulting in slightly lower savings than for the base case which has the boiler switched off and the electrical heater activated outside the heating season.

[3] 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.

[4] The insulation has a conductivity of 0.04 W/m.K and has a correction factor for “imperfection” of MAX(1.3, (2.0-Volume/10)).

[5] The settings for the controller for the charging of the store were kept constant for all variations (62°C start, 70°C stop).

[6] The boiler standby and supply set temperature were set to be 5K higher than the thermostat (off) setting. The thermostat had a constant hysteresis of 8K.

[7] The insulation has a conductivity of 0.04 W/m.K and the collector pipe size was12 mm external diameter. No correction factor for “imperfections” was included.

Presentation of Results

The results are presented with a sheet for each of the parameters described in the summary above. Each has a diagram where the values for the three fractional savings indicators is shown. In most diagrams the value for the base case is shown as a vertical dotted black line. The scales for fractional savings and for the x-axis (mainly heights in the store) have been kept the same for all diagrams (except for a few cases) so that the diagrams can be compared more easily.

Sections describing any differences to the base case, the results and additional comments follow the diagram.

All fractional energy savings are for the Task 26 reference system which assumes an annual efficiency (including standby losses of the boiler) of 85% for the boiler.

Sensitivity parameter :	Collector size [m^2] (fixed store size (0.73 m^3)	5 – 30 m^2

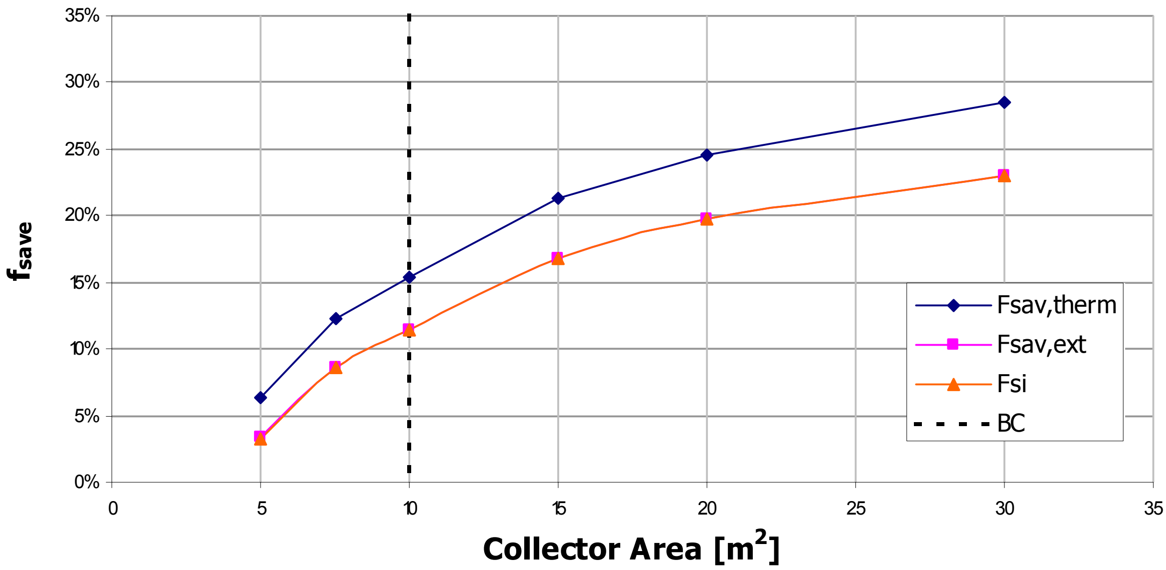


Fig. 2. Variation of fractional energy savings with collector size with fixed store volume of 0.73 m^3.

Differences from Base Case
None

Description of Results
As expected the increase of savings with increasing collector area decreases the larger the area. There are very few penalties incurred for the settings, so that $f_{si} \approx f_{sav,ext}$

Comments
None.

Sensitivity parameter :	Collector Size [m2] (fixed store spec. vol. 0.075 m^3/m^2)	5 – 30 m^2

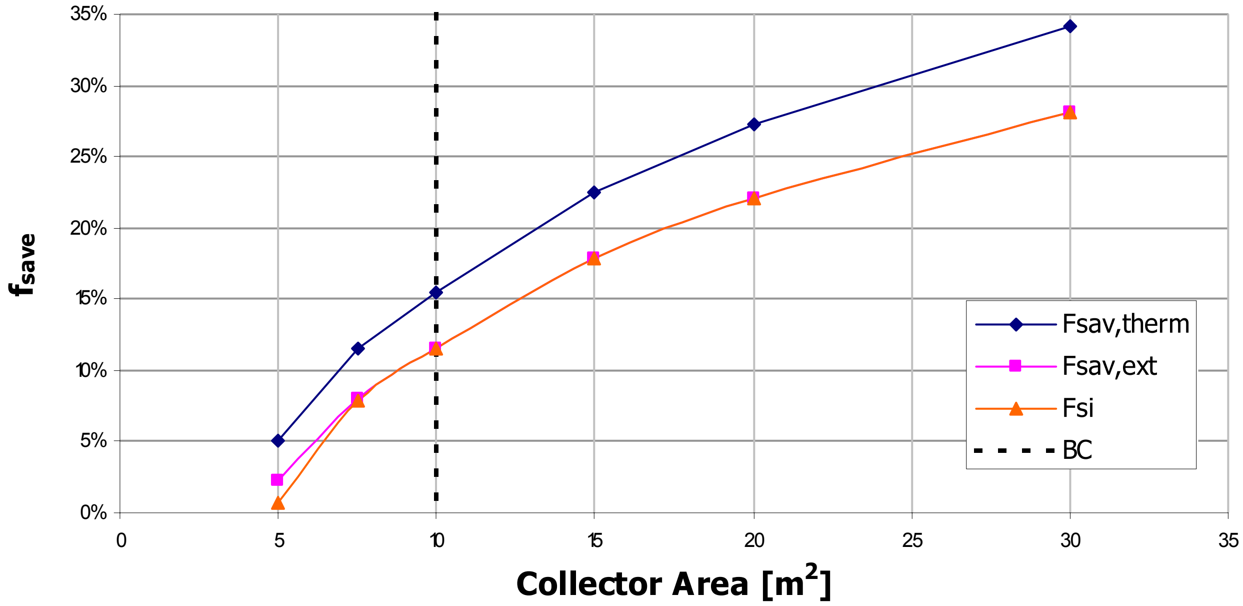


Fig. 3. Variation of fractional energy savings with collector size with fixed specific store volume of 0.075 m^3/m^2.

Differences from Base Case
The heights for the inlet of the lower DHW heat exchanger, the electrical heater and boiler outlet were all varied with the store volume so that:

- The volume heated by the auxiliary (below the outlet of the upper DHW heat exchanger) was always the same (0.25 m^3).
- A “dead” volume of 5% of the store volume exists above the upper DHW heat exchanger’s outlet.
- The sensors for the thermostats controlling the store charging and the electrical heater were always the same height above the outlet / heater (0.06 / 0.02).
- The height of the store was constant.
- The Heat loss coefficient for the store varied using equations for the area of the relevant section. In addition a volume sensitve “imperfection” factor was used to multiply the theoretical values. $UA_{loss,corr}$ = MAX(1.3, (2.0-Volume/10)).
- The heights (extension) of each heat exchanger was kept constant apart from when it was necessary to compress the collector and lower DHW heat exchangers so that they were under the boiler outlet position.

Description of Results
As expected the increase of savings with increasing collector area decreases the larger the area. There are very few penalties incurred for the settings, apart from for the smallest store/collector area, so that $f_{si} \approx f_{sav,ext}$

Comments
None.

Sensitivity parameter :	Store Size [m3] (fixed collector area of 10 m²)	0.3 – 3.0 m³

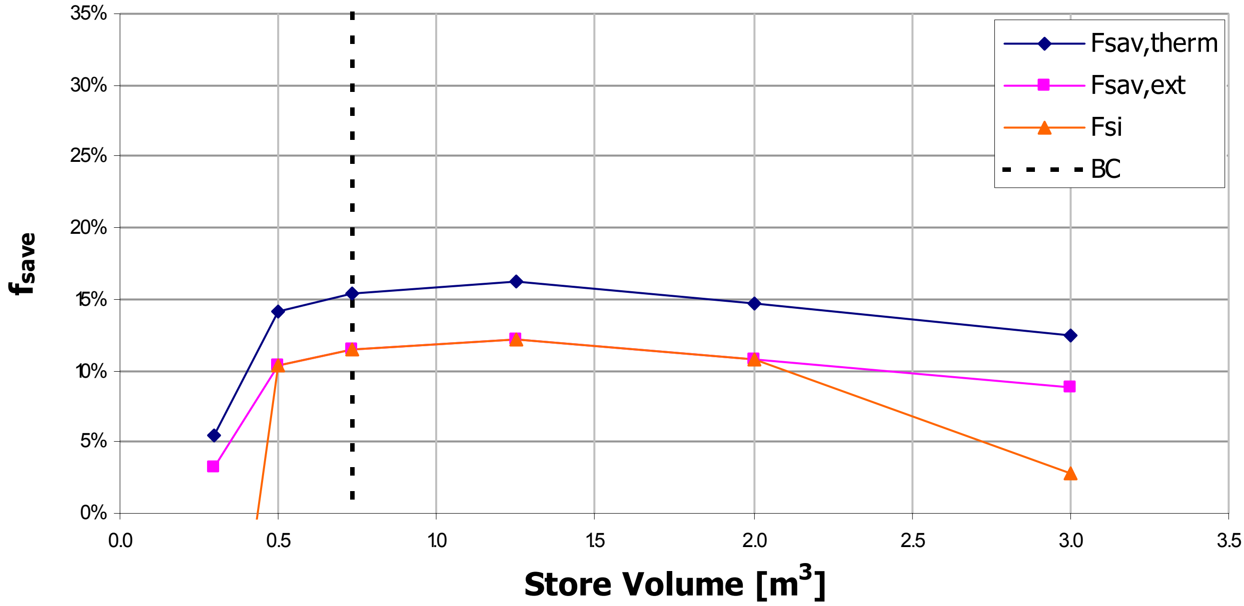


Fig. 4. Variation of fractional energy savings with store volume with fixed collector area of 10 m^2.

Differences from Base Case
The heights for the inlet of the lower DHW heat exchanger, the electrical heater and boiler outlet were all varied with the store volume so that:

- The volume heated by the auxiliary and below the outlet of the upper DHW heat exchanger was always the same (0.25 m^3).
- A "dead" volume of 5% of the store volume exists above the upper DHW heat exchanger's outlet.
- The sensors for the thermostats controlling the store charging and the electrical heater were always the same height above the outlet / heater (0.06 / 0.02).
- The height of the store was constant.
- The Heat loss coefficient for the store varied using equations for the area of the relevant section. In addition a volume sensitive "imperfection" factor was used to multiply the theoretical values. $UA_{loss,corr}$ = MAX(1.3, (2.0-Volume/10)).
- The heights (extension) of each heat exchanger was kept constant apart from when it was necessary to compress the collector and lower DHW heat exchangers so that they were under the boiler outlet position.

Description of Results
Here the savings show an optimum at around 1.25 m^3 for the settings used. Below this value the store is too small to be able to utilise the solar 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 (year round) start to outweigh the gain in utilised solar heat and the overall savings decrease again. The dips in the f_{si} curve are due to penalties for the DHW preparation. For the 3.0 m^3 case, this is due to the fact that the position of the upper DHW heat exchanger has not been moved and that only half of it lies in the heated volume, thus limiting its effectivity.

Comments
None.

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

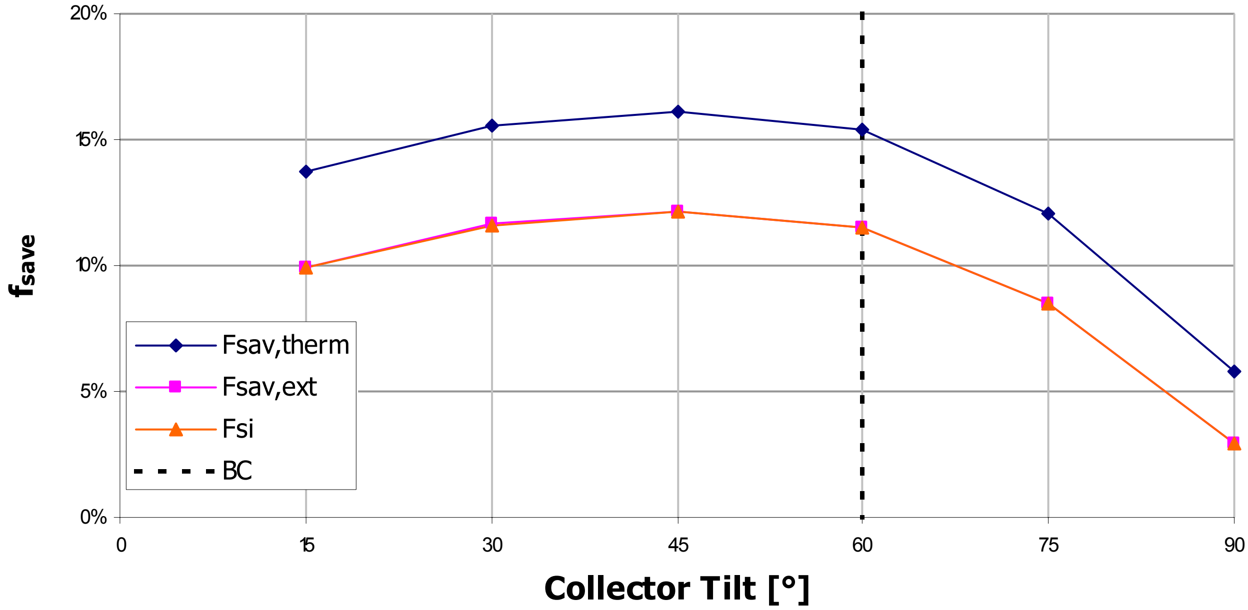


Fig. 5. Variation of fractional energy savings with collector tilt, with fixed azimuth angle of 0°.

Differences from Base Case
None

Description of Results
Here the savings show an optimum at around 45° tilt. This is dependent on the climate and load data. Generally, the larger the space heating load in relation to the DHW load, the higher the optimum tilt angle.

Comments
None.

Sensitivity parameter :	Climate and Building	-

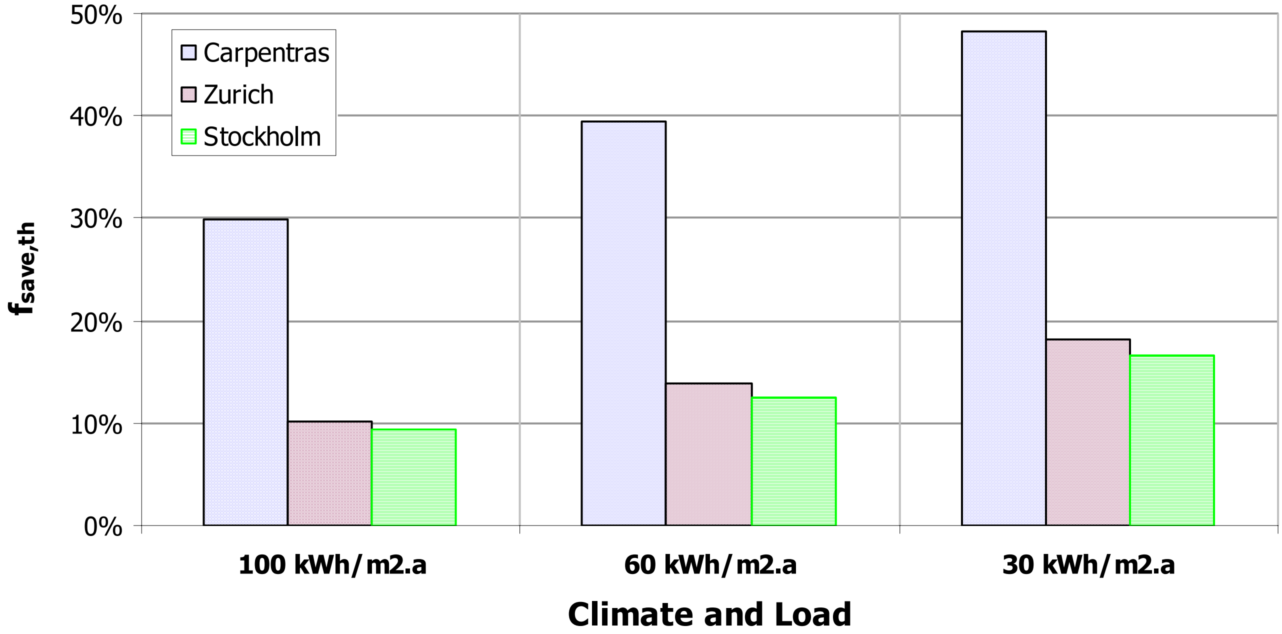


Fig. 6. Variation of thermal fractional energy savings with climate and building.

Differences from Base Case

In these simulations, the electrical heater was not activated at all during the non-heating season and the boiler was activated the whole time. In the base case the boiler is switched off outside of the heating season and the electrical heater in the store is used as auxiliary. For the Zurich climate and 60 kWh/m^2.yr house this results in approximately 2%-points lower fractional savings. For larger solar fractions this difference would be greater.

Description of Results

The results show that the Carpentras climate is much better than the other two. Results for Stockholm and Zurich are quite similar despite the large geographic separation in latitude. This is more the case for $f_{sav,ext}$ and f_{si} than for $f_{sav,therm}$ since roughly the same amount of electricity is used in both cases.

Comments

None.

Sensitivity parameter :	Collector Heat Exchanger Outlet Rel. Height [-]	0.000 – 0.236

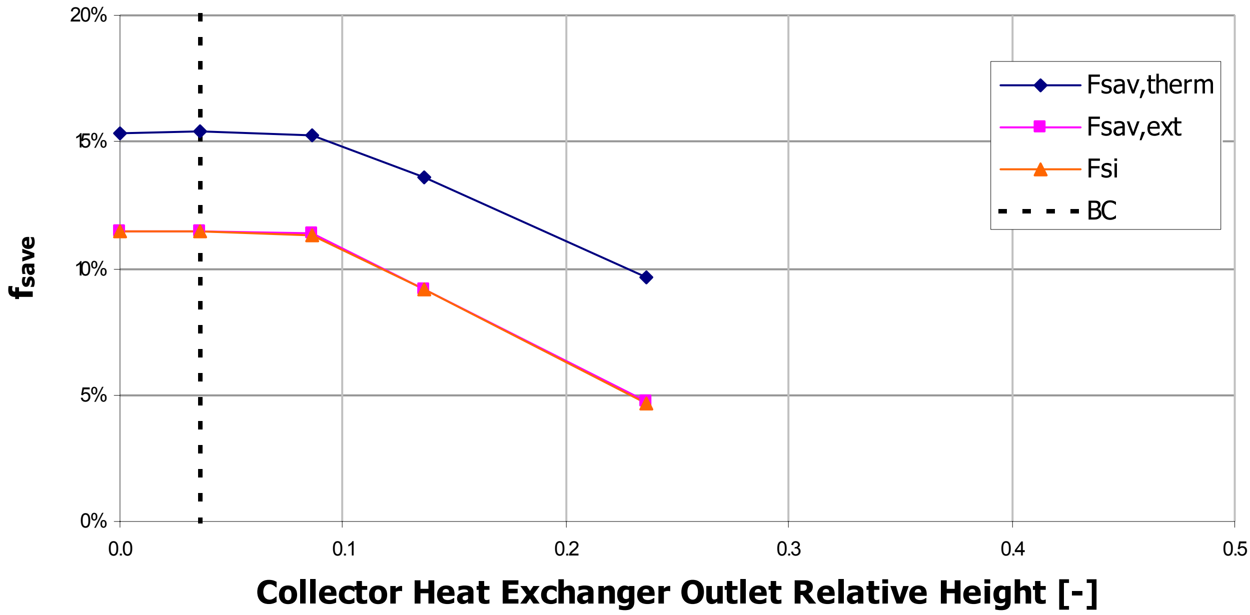


Fig. 7. Variation of fractional energy savings with the position of the collector heat exchanger's outlet, with fixed vertical extension of 0.16 for the heat exchanger. Heights are relative heights (=actual height / total height of store)

Differences from Base Case
None

Description of Results
Here the savings are constant up until an outlet height of about 0.1 and then they drop quickly above this point. The position of the lower DHW heat exchanger was unchanged during these simulations. Expected results were that the lower the heat exchanger the better savings, as the volume of the store is best utilised with minimum "dead" volume. However, it does not appear to be too critical to position the heat exchanger as low as possible as long as it is lower than 0.1 for the outlet. It is assumed that if the heat exchanger were compressed (lesser vertical extent) then this would improve performance slightly due to there being slightly larger volume available to solar.

Comments
None.

Sensitivity parameter :	Lower DHW Heat Exchanger Inlet Rel. Height [-]	0.100 – 0.500

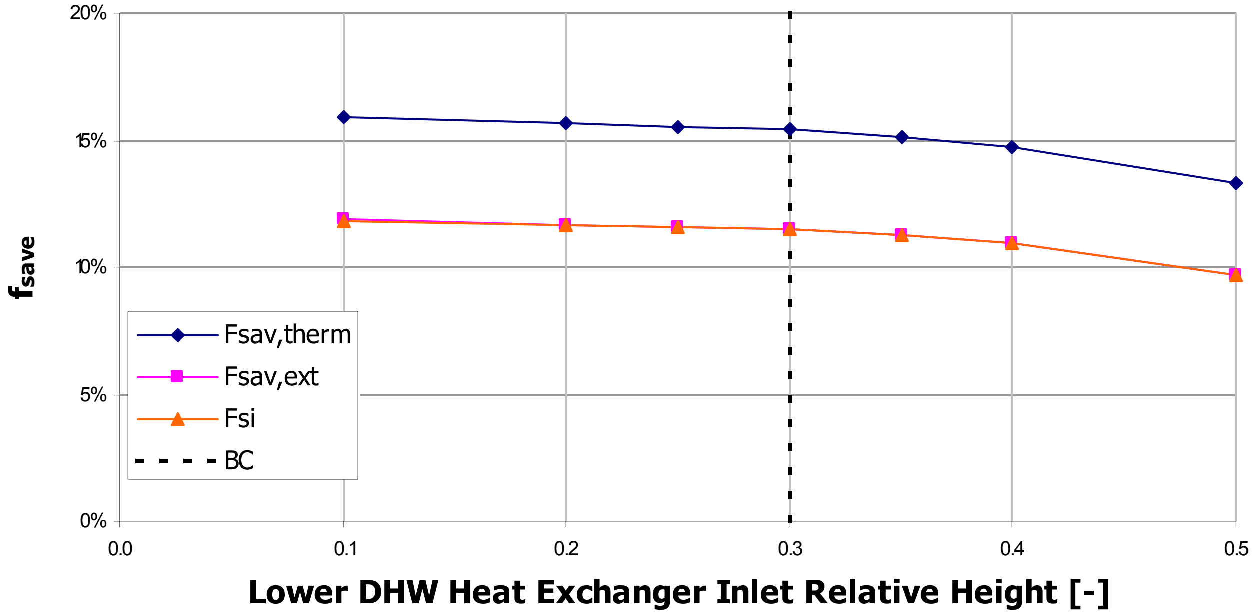


Fig. 8. Variation of fractional energy savings with the position of the lower DHW heat exchanger's inlet, with fixed vertical extension of 0.16 for the heat exchanger. Heights are relative heights (=actual height / total height of store)

Differences from Base Case
None

Description of Results
As with the collector heat exchanger, the savings are relatively constant for lower heights (below 0.3), although here the savings increase marginally over this region. Above about 0.35 for the inlet height, the savings decrease much faster, although not as quickly as for the collector heat exchanger.

Comments
None.

Sensitivity parameter :	Upper DHW Heat Exchanger Outlet Rel. Height [-]	0.850 – 1.000

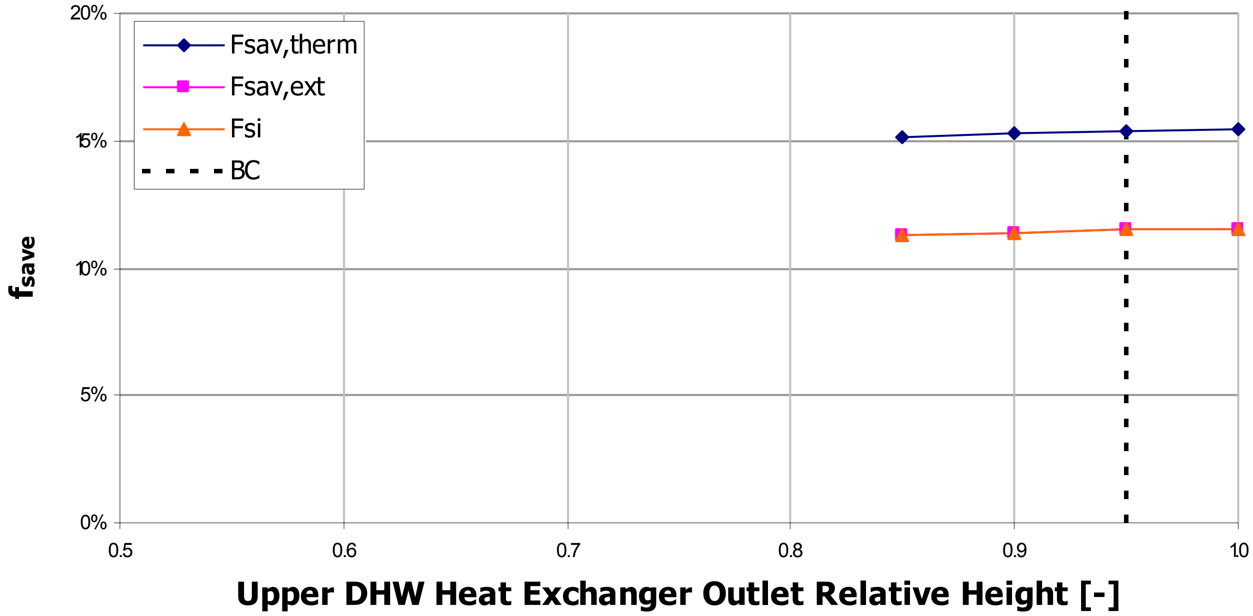


Fig. 9. Variation of fractional energy savings with the position of the upper DHW heat exchanger's outlet, with fixed vertical extension of 0.16 for the heat exchanger. Heights are relative heights (=actual height / total height of store)

Differences from Base Case
None

Description of Results
Again the savings vary only slightly over the range of values simulated, the increase in savings decreasing with increasing height. It is expected that the best position is at the very top of the store as this gives minimum "dead" volume.

Comments
The thermostat/controller settings for auxiliary charging of the store were unchanged for these simulations. Adjusting these settings so that the peak load is just covered would probably alter the results shown here and lead to a larger variation in savings. The position of the boiler outlet / electrical heater was not changed.

Sensitivity parameter :	Boiler Inlet Rel. Height [-]	0.749 – 0.999

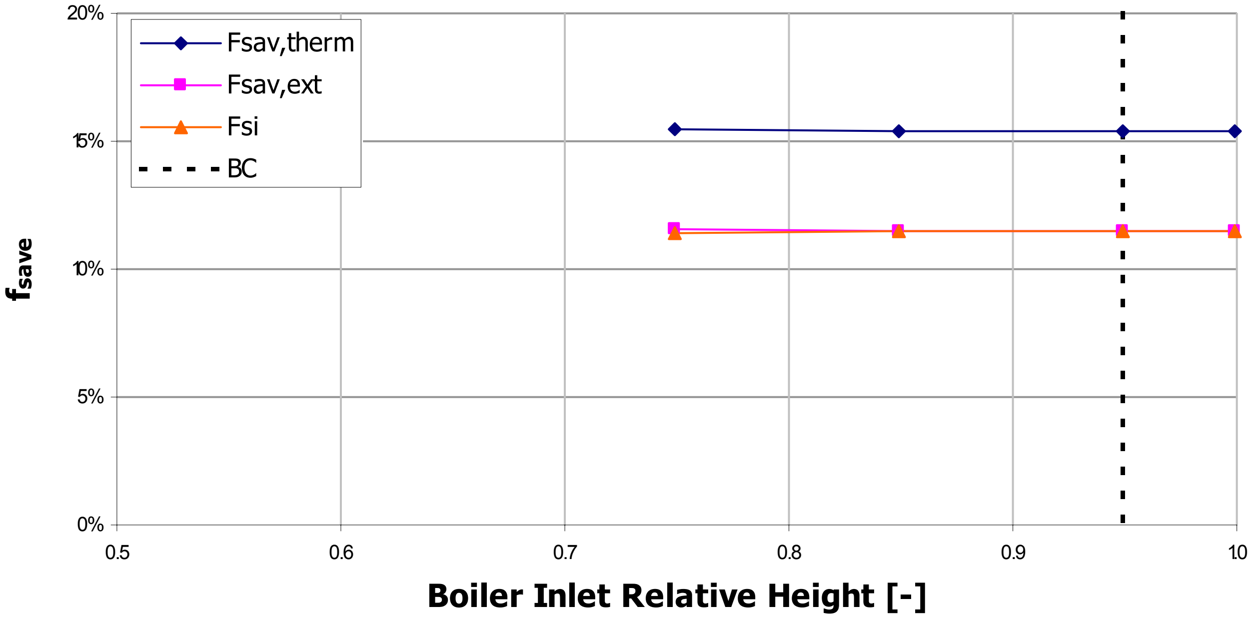


Fig. 10. Variation of fractional energy savings with the position of the boiler inlet. Heights are relative heights (=actual height / total height of store)

Differences from Base Case
None

Description of Results
Again the savings vary insignificantly over the range of values simulated.

Comments
The thermostat/controller settings for auxiliary charging of the store were unchanged for these simulations.

Sensitivity parameter :	Boiler Outlet & Electrical Heater Rel. Height [-]	0.407 – 0.807

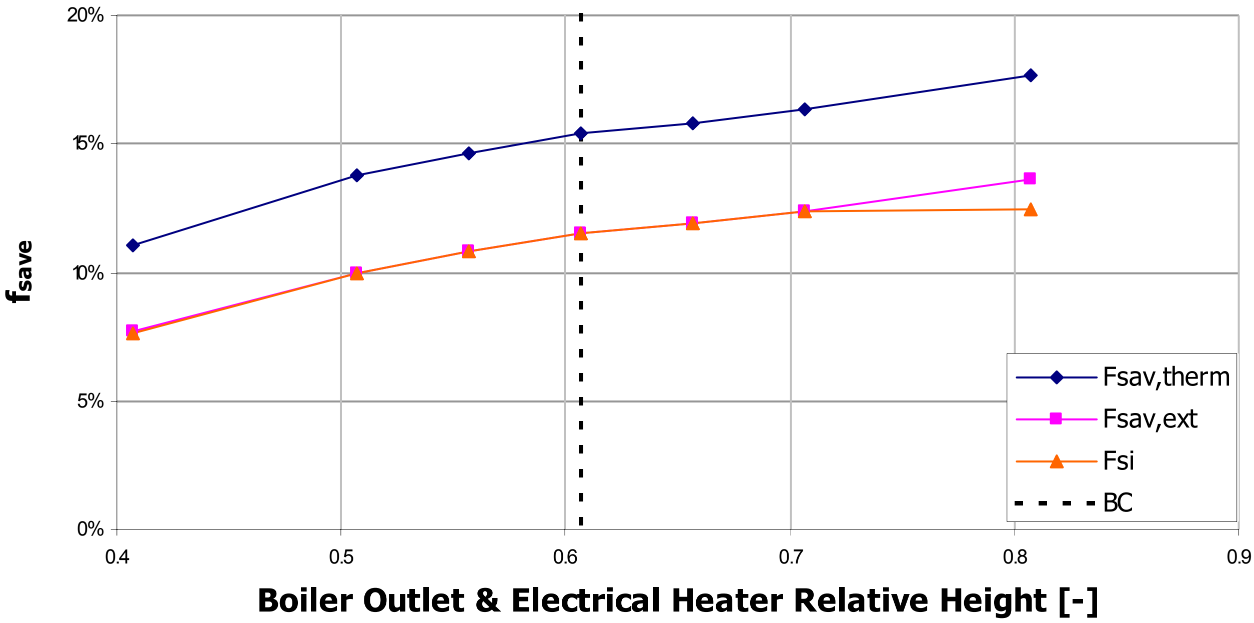


Fig. 11. Variation of fractional energy savings with the position of the boiler outlet and electrical heater. Heights are relative heights (=actual height / total height of store)

Differences from Base Case
None

Description of Results
The savings increase significantly with a higher position of the outlet. Above a height of 0.7 the savings indicator levels off and would probably drop for even higher values as penalties start occurring for the DHW load not being met in full.

Comments
The thermostat/controller settings for auxiliary charging of the store were unchanged for these simulations. Adjusting these settings so that the peak load is just covered would probably alter the results shown here and lead to a smaller variation in savings and maybe even an optimum.

The results are likely to be load dependent.

Sensitivity parameter :	Heading System Inlet Rel. Height [-]	0.000 – 0.500

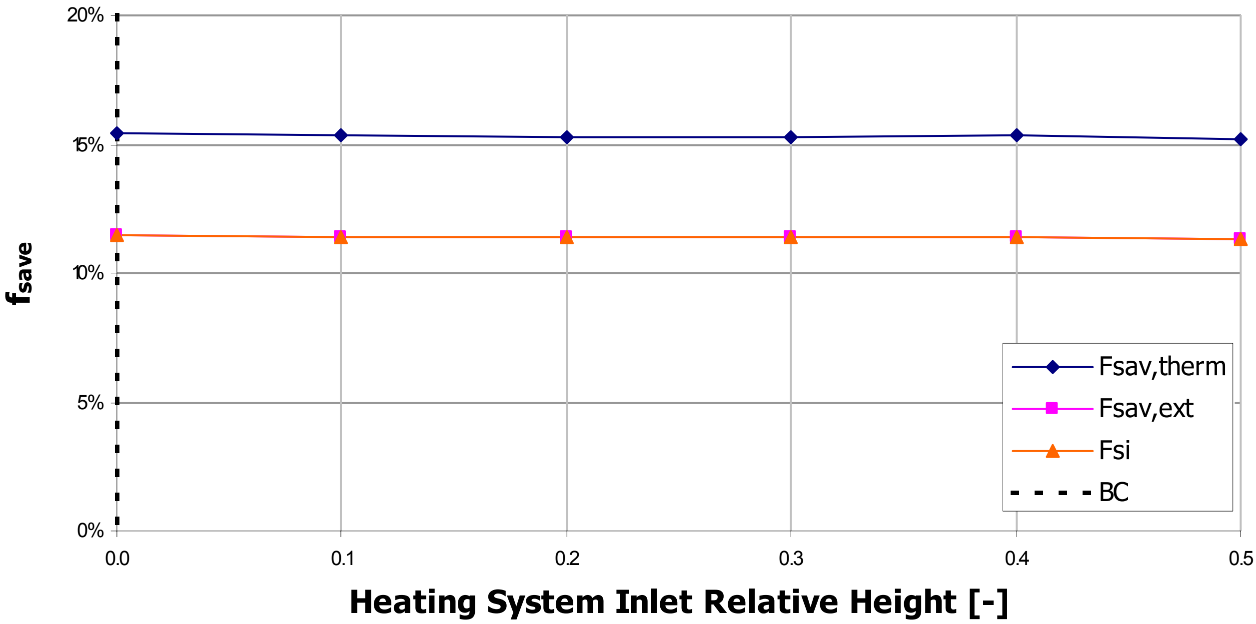


Fig. 12. Variation of fractional energy savings with the position of the heating system inlet (return). Heights are relative heights (=actual height / total height of store)

Differences from Base Case
None

Description of Results
There is virtually no variation of the savings with this parameter over the range simulated (half the store).

Comments
None.

Sensitivity parameter :	Heading System Outlet Rel. Height [-]	0.715 – 1.000

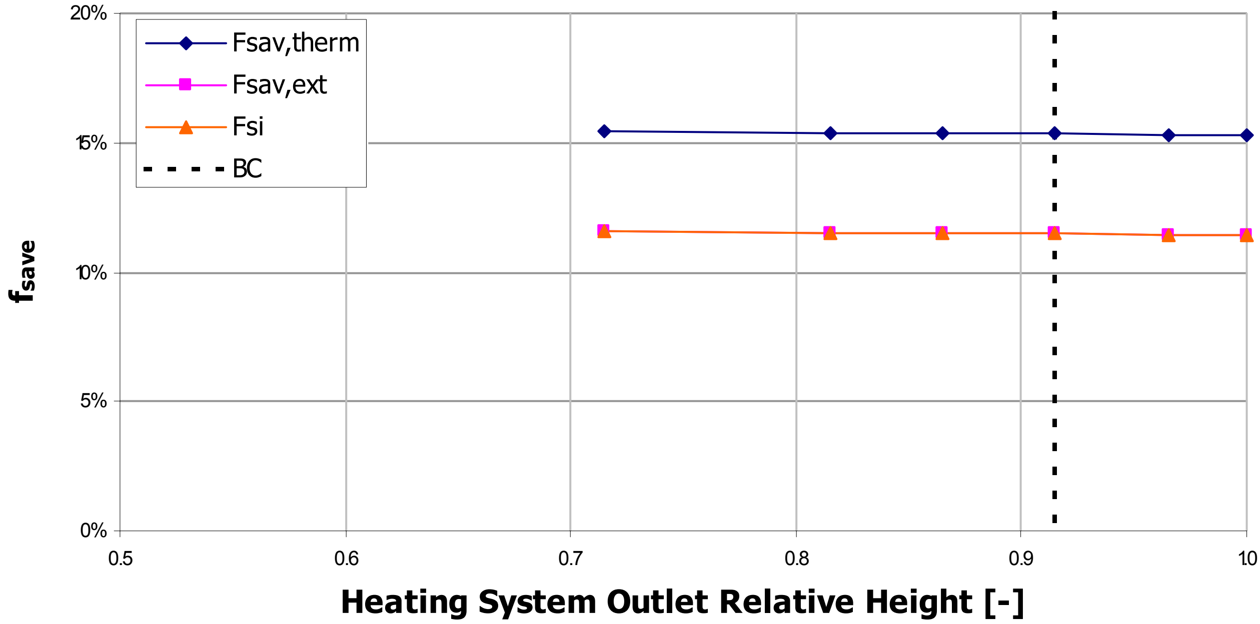


Fig. 13. Variation of fractional energy savings with the position of the heating system outlet (forward). Heights are relative heights (=actual height / total height of store)

Differences from Base Case
None

Description of Results
Again there is virtually no variation of the savings with this parameter over the range simulated (third of the store).

Comments
None.

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

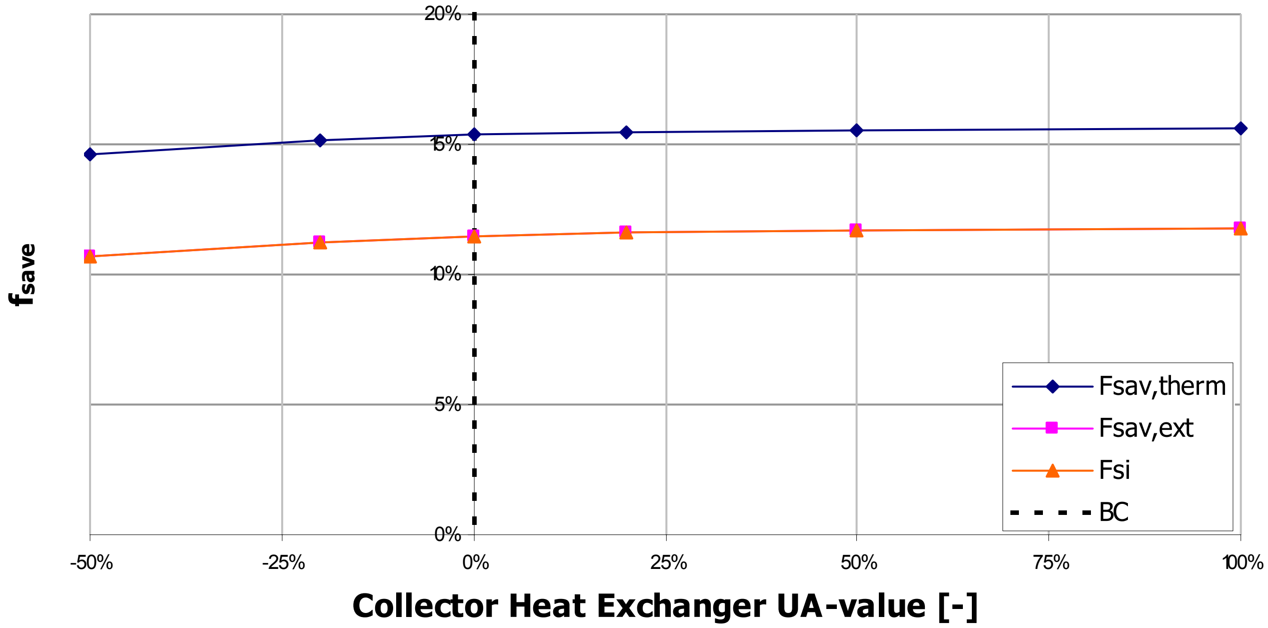


Fig. 14. Variation of fractional energy savings with the UA-value of the collector heat exchanger. Parameter values are relative to that identified for the system from measurements.

Differences from Base Case
None

Description of Results
Below the base case value (identified from measurements), the savings decrease more and more rapidly. Above this value there is only a marginal improvement in the savings.

Comments
None.

Sensitivity parameter :	Lower DHW Heat Exch. UA (variation from identified value)	-50% - +100%

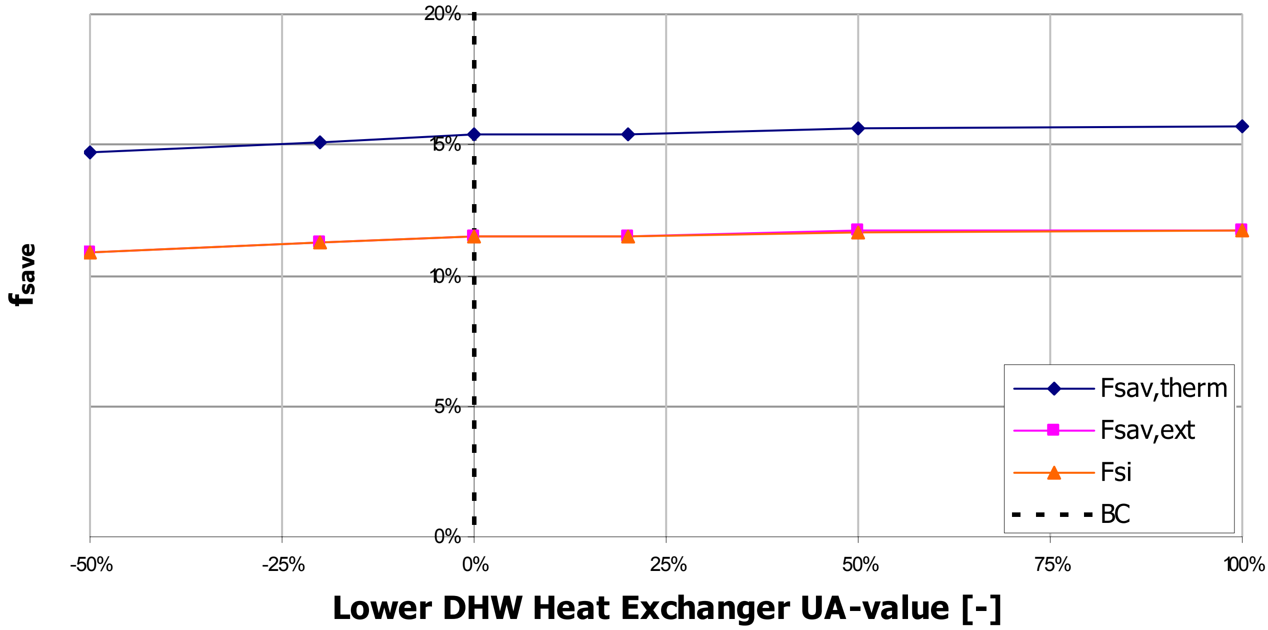


Fig. 15. Variation of fractional energy savings with the UA-value of the lower DHW heat exchanger. Parameter values are relative to that identified for the system from measurements.

Differences from Base Case
None

Description of Results
Below the base case value (identified from measurements), the savings decrease more rapidly. Above this value there is only a slight improvement in the savings.

Comments
The thermostat/controller settings for auxiliary charging of the store were unchanged for these simulations. Adjusting these settings so that the peak load is just covered would probably alter the results shown here.

Sensitivity parameter :	Upper DHW Heat Exch. UA (variation from identified value)	-50% - +100%

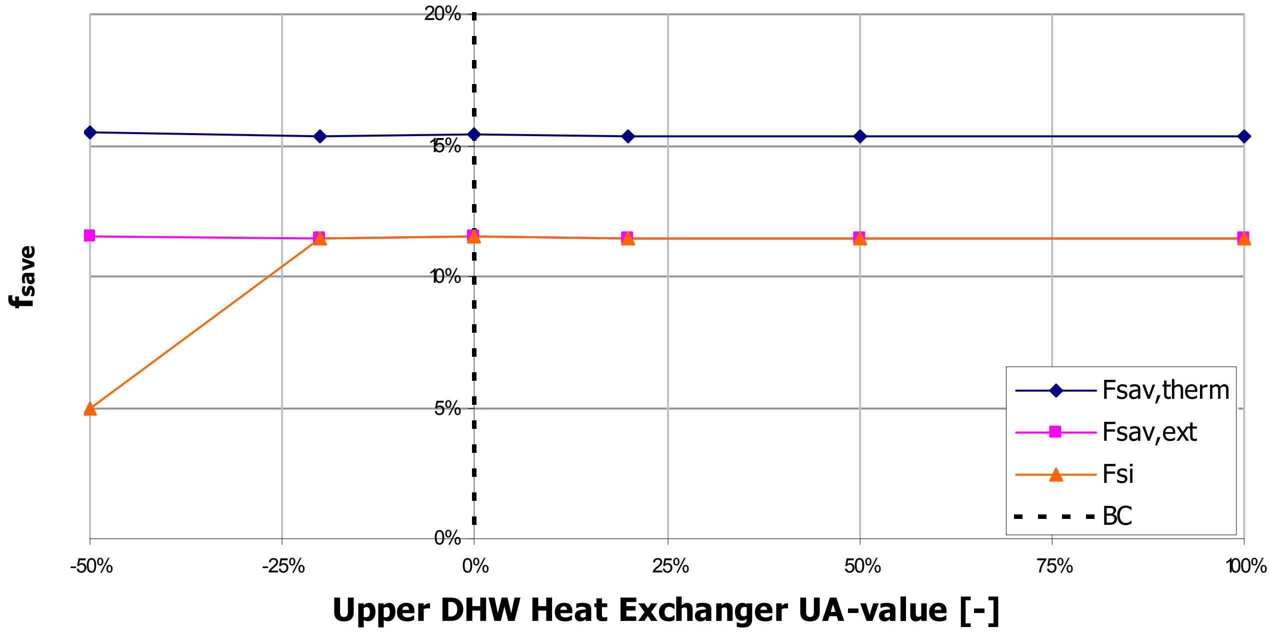


Fig. 16. Variation of fractional energy savings with the UA-value of the upper DHW heat exchanger. Parameter values are relative to that identified for the system from measurements.

Differences from Base Case
None

Description of Results
There are no significant variations in $f_{sav,therm}$ and $f_{sav,ext}$ over the range simulated. However, f_{si} shows that there is a lower limit below which large penalties occur due to the DHW load not being met in full.

Comments
The thermostat/controller settings for auxiliary charging of the store were unchanged for these simulations. Adjusting these settings so that the peak load is just covered would probably alter the results shown here and most likely lead to significant variations in savings.

Sensitivity parameter :	Store Insulation: top [cm]	4 – 18 cm

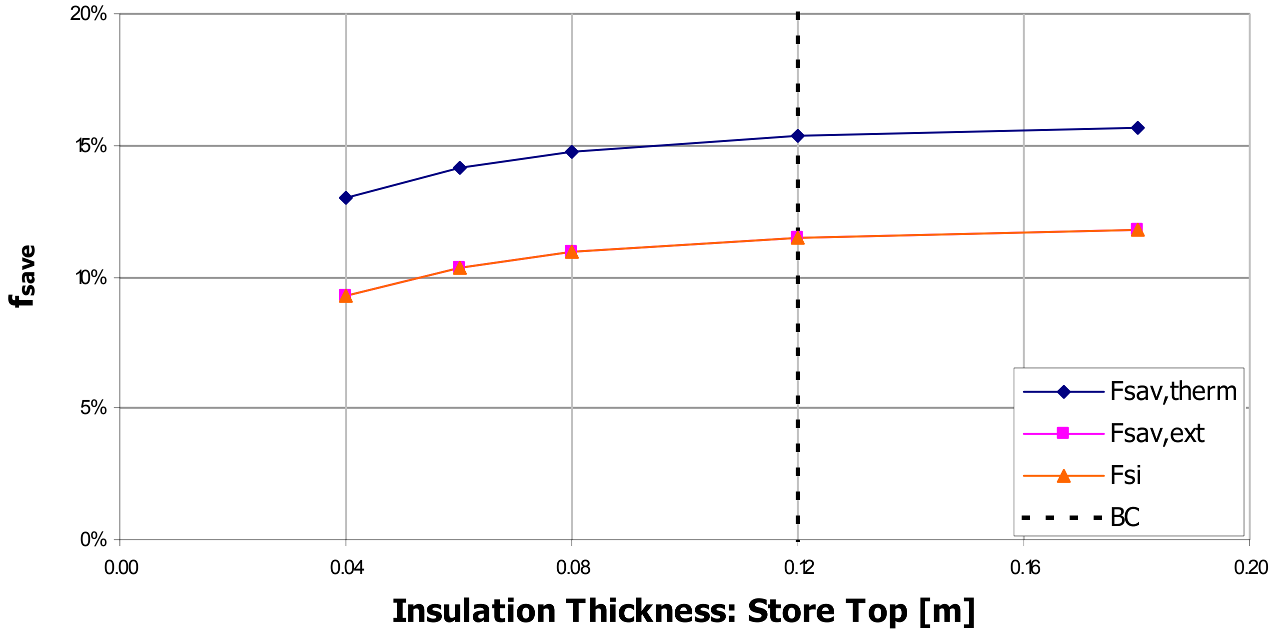


Fig. 17. Variation of fractional energy savings with the thickness of insulation on the top of the store.

Differences from Base Case
None

Description of Results
Above the base case thickness of 12 cm there is only a slight increase in savings. Below this thickness however, and especially below 8 cm, the savings start to decrease significantly.

Comments
The insulation has a conductivity of 0.04 W/m.K and has a correction factor for "imperfection" with the factor MAX(1.3, (2.0-Volume/10)). This is 1.93 for the base case volume of 0.73 m^3.

Sensitivity parameter :	Store Insulation: sides [cm]	4 – 18 cm

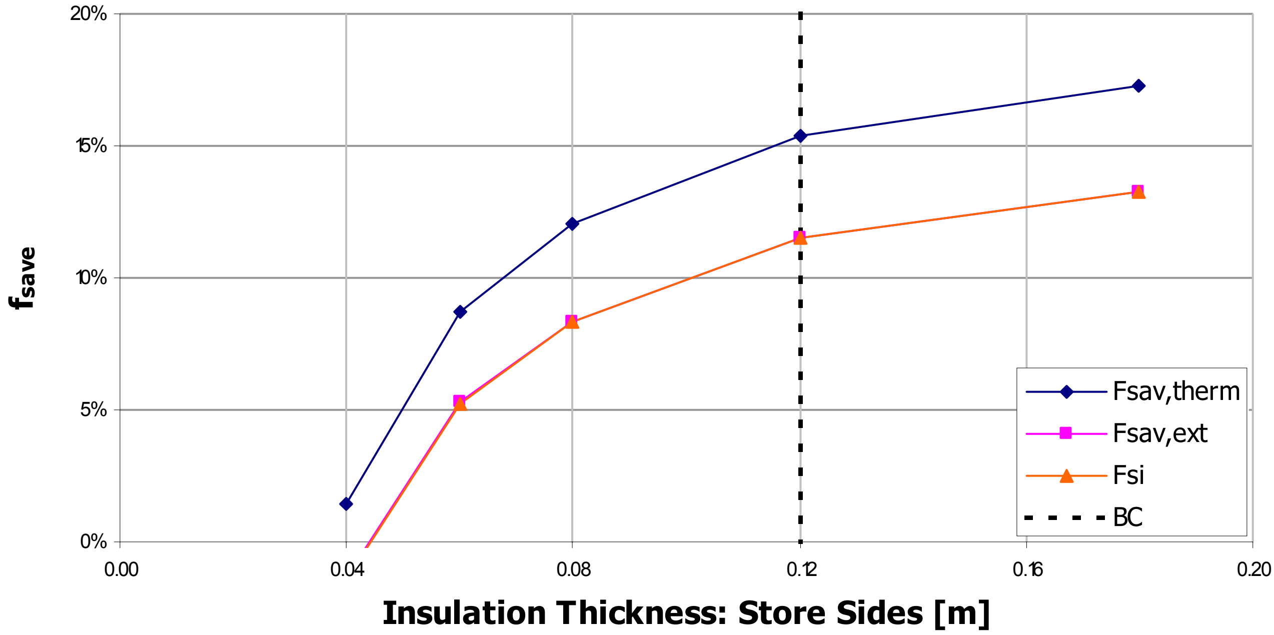


Fig. 18. Variation of fractional energy savings with the thickness of insulation on the sides of the store.

Differences from Base Case
None

Description of Results
Here the variation of insulation thickness is highly significant over the whole range simulated.

Comments
The insulation has a conductivity of 0.04 W/m.K and has a correction factor for "imperfection" with the factor MAX(1.3, (2.0-Volume/10)). This is 1.93 for the base case volume of 0.73 m^3.

Sensitivity parameter :	Store Insulation: bottom [cm]	4 – 18 cm

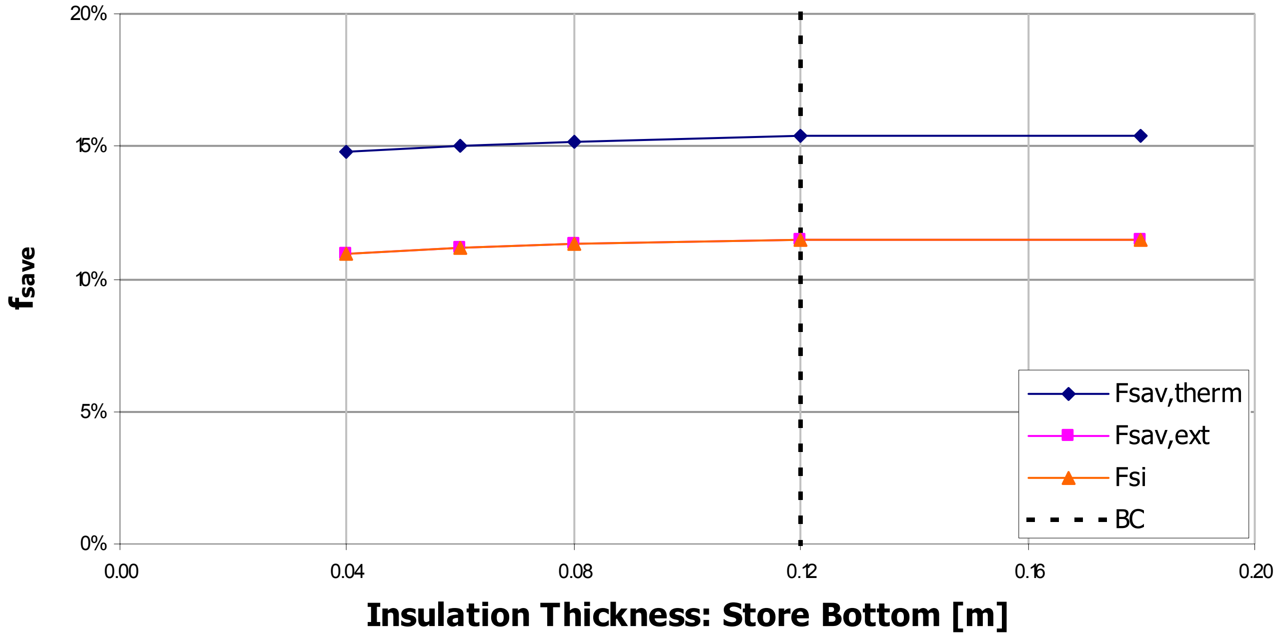


Fig. 19. Variation of fractional energy savings with the thickness of insulation on the bottom of the store.

Differences from Base Case
None

Description of Results
Above the base case value of 12 cm there is no significant improvement in savings. Below 8 cm, the decrease in savings is significant.

Comments
The insulation has a conductivity of 0.04 W/m.K and has a correction factor for "imperfection" with the factor MAX(1.3, (2.0-Volume/10)). This is 1.93 for the base case volume of 0.73 m^3.

Sensitivity parameter :	Store Insulation: whole store [cm]	4 – 18 cm

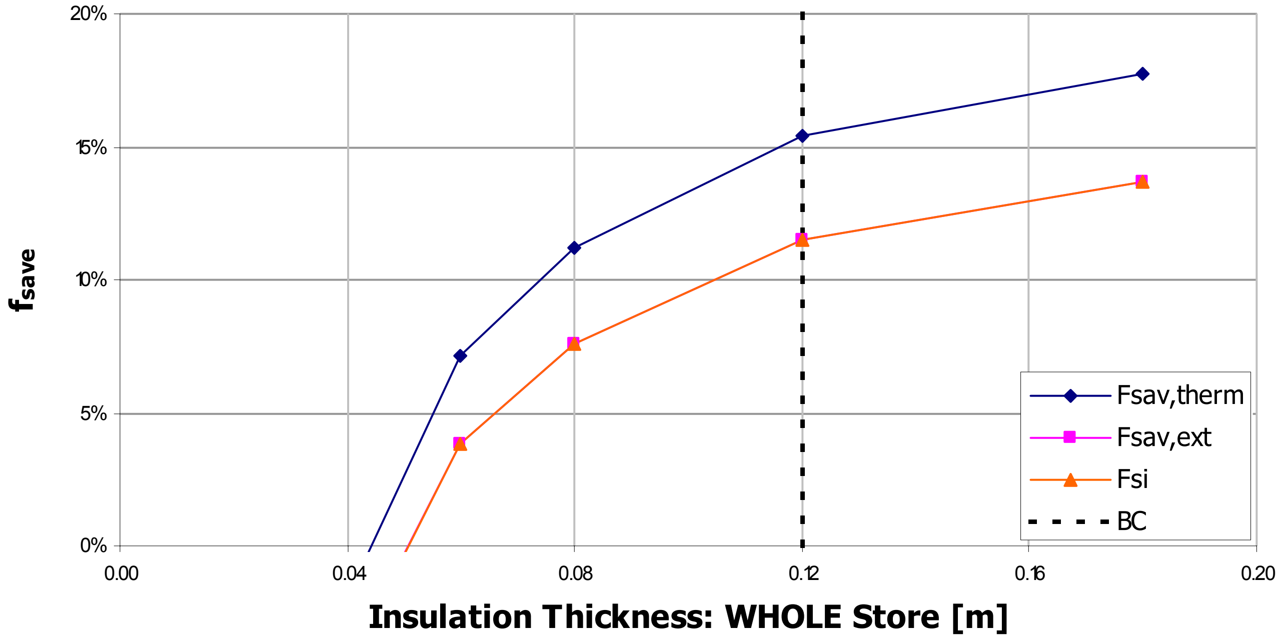


Fig. 20. Variation of fractional energy savings with the thickness of insulation around the whole store.

Differences from Base Case
None

Description of Results
Here the variation of insulation thickness is highly significant over the whole range simulated.

Comments
The insulation has a conductivity of 0.04 W/m.K and has a correction factor for "imperfection" with the factor MAX(1.3, (2.0-Volume/10)). This is 1.93 for the base case volume of 0.73 m^3.

Sensitivity parameter :	Store Insulation [-] (for stores measured in lab)	-

Fig. 21. Variation of fractional energy savings with the heat loss values for stores of about the same volume as the base case store. The heat loss values have been identified from measurements.

Differences from Base Case
None

Description of Results
Here there is a significant variation in savings. Types 1 and 2 are commonly used methods for insulation whereas 3 is "home built" at SERC, but very simple. BC is the base case system with 12 cm of good insulation, but with an imperfection factor of 1.93.

Comments
The heat loss coefficients for the three other stores have been derived using parameter identification for three stores with volumes in the range 0.73 – 0.77 m^3. These stores have different thicknesses and types of insulation as follows:

1. Rock wool (approx: 12 cm) wrapped around the store and then enclosed with a home made wooden box (1 m x 1m), with loose insulation stuffed into the corners. Open expansion vessel on top of store. Several connections through the insulation. Standard methods used in self-built systems in Sweden.
2. Approx: 12 cm foam insulation wrapped around whole store. Plastic cover stopping air leaks from the insulation. One thermal bridge where a flat plate heat exchanger was mounted inside the insulation and the insulation thickness was much smaller. All connections at the bottom – nothing through the insulation. Closed expansion vessel with outlet from bottom of store.
3. Loose, small polystyrene particles filling a plastic "tarpaulin" cover, with approx. thickness of 20-30 cm (varies with height as the cover bulges in the middle, and the cover is not perfectly centred). All connections at the bottom – nothing through the insulation. Closed expansion vessel with outlet from bottom of store.

Sensitivity parameter :	Collector Controller dT_{start} [K] (constant dTstart/dTstop)	4 – 12 K

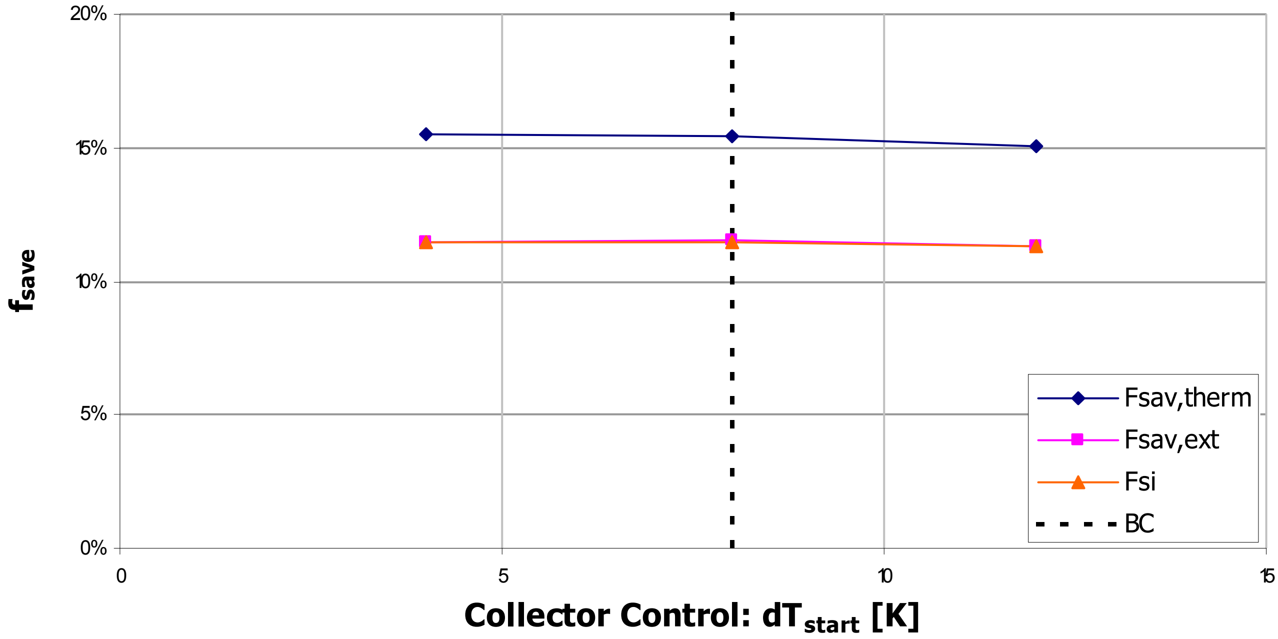


Fig. 22. Variation of fractional energy savings with the collector controller settings.

Differences from Base Case
None

Description of Results
Here there is slight decrease in performance with increasing dT_{start}, however the difference between the values for 4 and 8 K is very small.

Comments
The ratio of the upper and lower deadbands for the controller was kept constant at 8 for these simulations so as to avoid instability.

Sensitivity parameter :	Boiler Internal Standby Temperature [C]	75 - 90°C

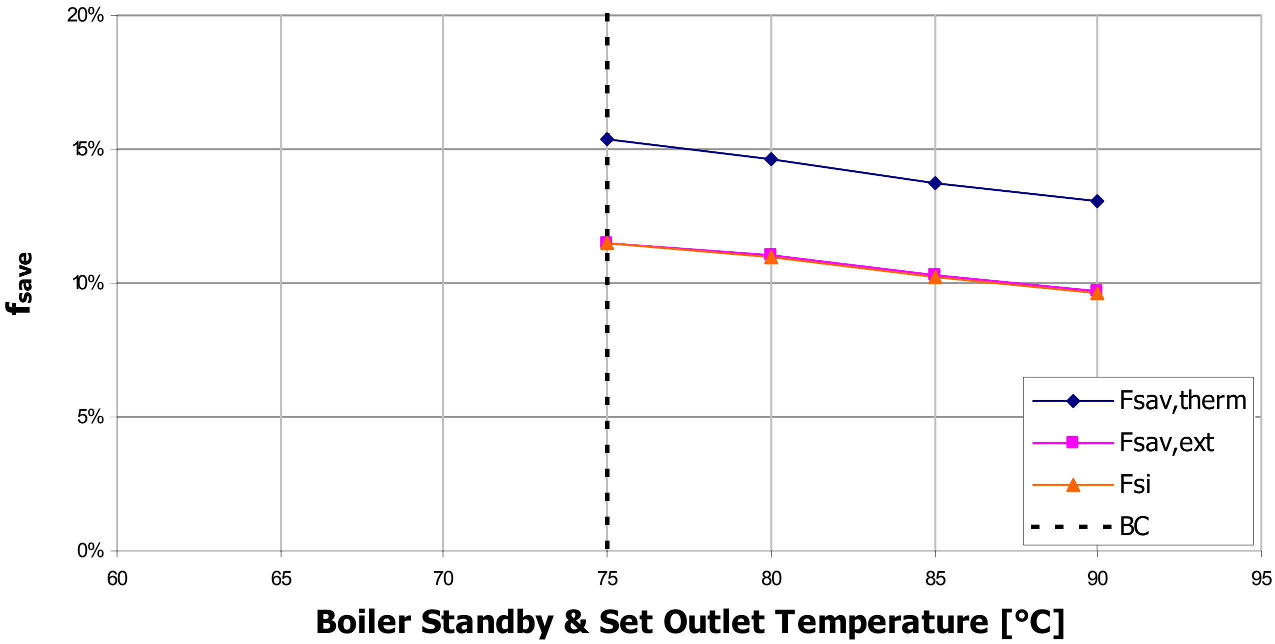


Fig. 23. Variation of fractional energy savings with the internal standby temperature of the oil boiler. This is also the set outlet temperature of the boiler.

Differences from Base Case
None

Description of Results
Here there is significant deterioration in performance with increased standby temperature. This is due to increase losses during standby as well as during combustion.

Comments
The settings for the controller for the charging of the store were kept constant for all variations (62°C start, 70°C stop).

Sensitivity parameter :	Store Charge/Electrical Heater Thermostat (off) [°C]	60 - 80°C

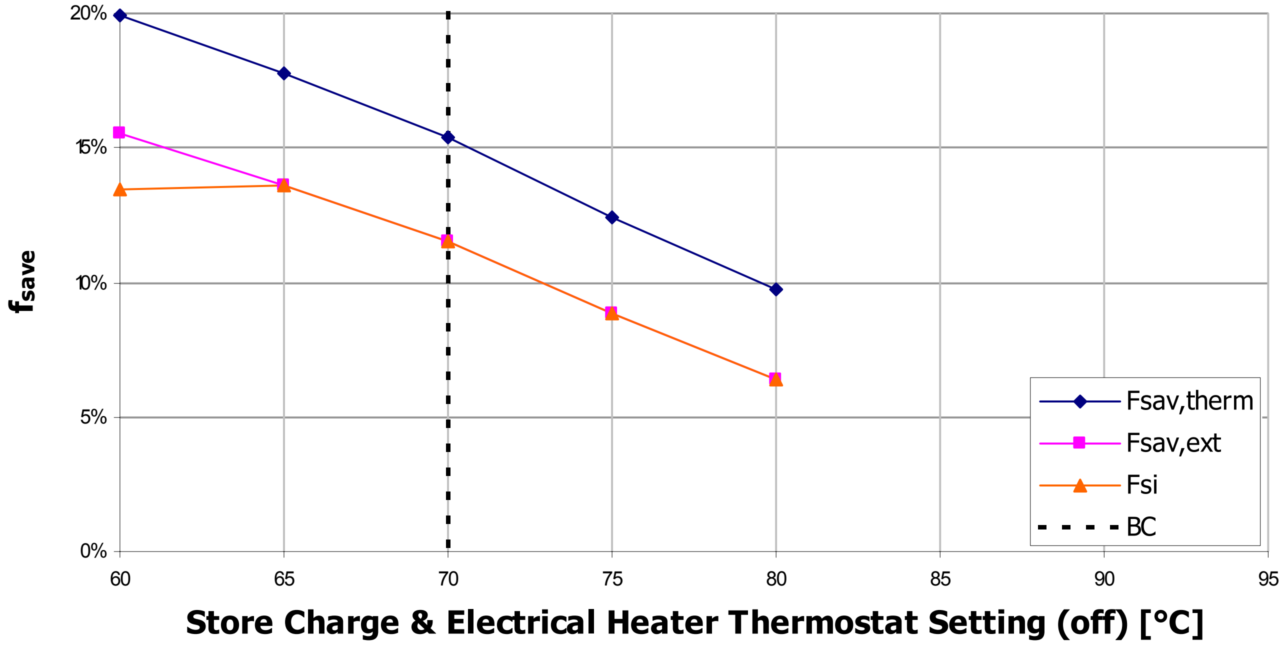


Fig. 24. Variation of fractional energy savings with the store charge controller settings. Values shown are for the charge turn off (upper bound) of the controller.

Differences from Base Case
None

Description of Results
Here there is significant deterioration in performance with increased standby temperature. This is due to increased losses in the store as well as greater losses from the boiler during standby and combustion. The overall annual boiler efficiency (η_{all}) ranged from 79.7% to 83.3%. However, it is not certain that the boiler can be run at temperatures of 65-70°C as many manufacturers state a minimum operating temperature for their products.

It is noticeable that f_{si} starts decreasing below a setting of 65°C whereas the others ($f_{sav,therm}$ and $f_{sav,ext}$) continue to increase. This is due to the penalty associated with the DHW load not being fully met.

Comments
The boiler standby and supply set temperature were set to be 5K higher than the thermostat (off) setting. The store charge controller and electrical heater thermostat had a constant hysteresis of 8K.

Sensitivity parameter :	Store Charge Flow Rate [kg/h]	400 –1200 kg/h

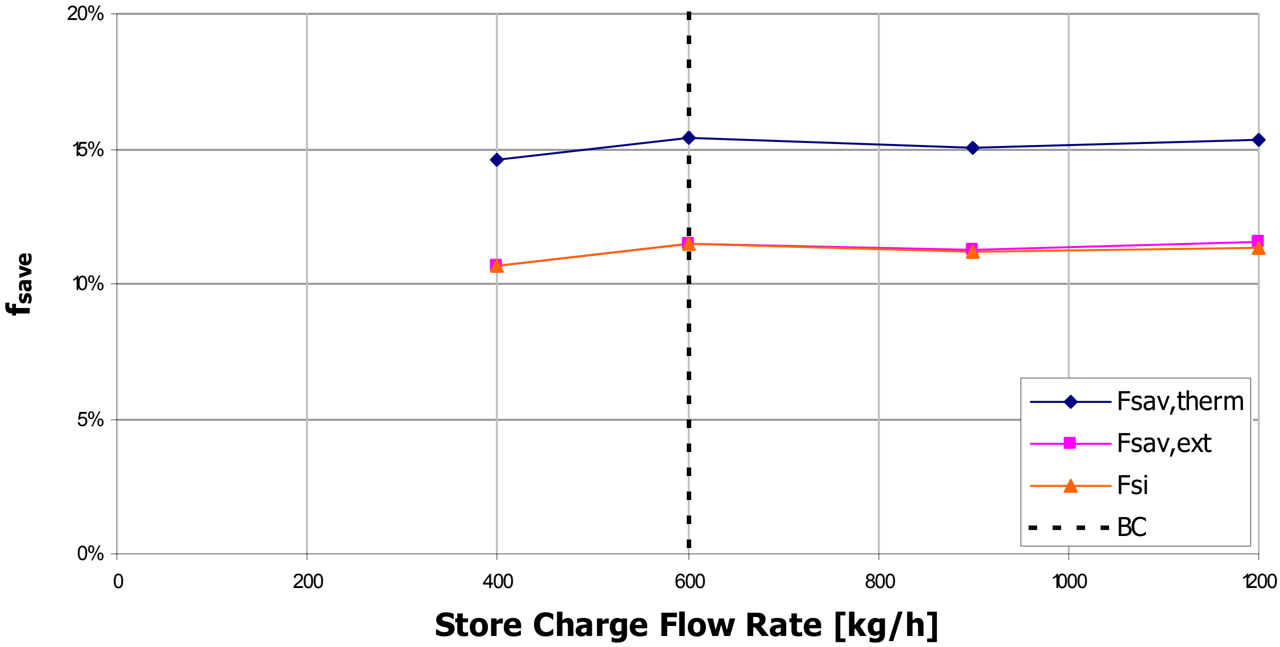


Fig. 25. Variation of fractional energy savings with the store charge flow rate.

Differences from Base Case
None

Description of Results
The store charge flow affects the annual savings slightly. The trend is for larger flows to give larger savings, but there are slight variations due to the variability in convergence of the simulation (see below).

Comments
Due to the allowed tolerance of convergence in the simulations, the energy balance for the boiler (heat supplied to the water – heat supplied to the store – standby losses from the boiler) varied by ±20 kWh which is enough to make the trend non-smooth.

Sensitivity parameter :	Store Charge Controller Sensor Rel. Height [-]	0.627 – 0.787

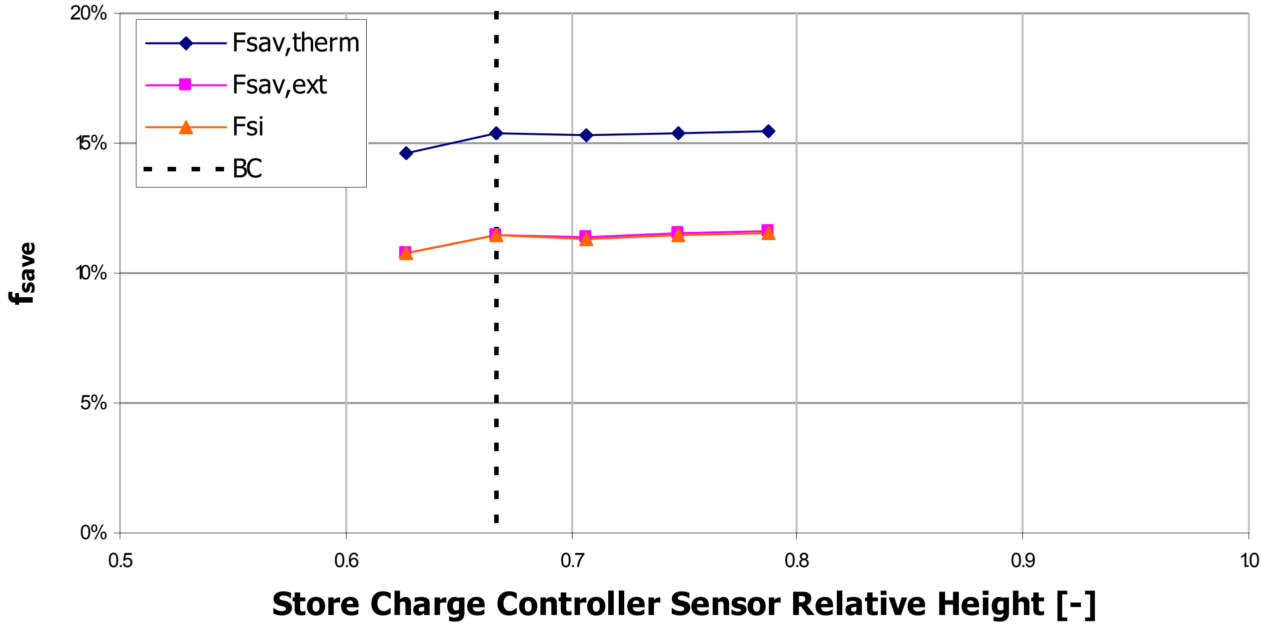


Fig. 26. Variation of fractional energy savings with the store charge controller's sensor position.

Differences from Base Case
None

Description of Results
Here there is a trend for the savings to improve with increasing sensor height, but that the improvements rate decreases with height. Again the trend is not smooth due to variation in the energy balance for the boiler.

Comments
Due to the allowed tolerance of convergence in the simulations, the energy balance for the boiler (heat supplied to the water – heat supplied to the store – standby losses from the boiler) varied by ±20 kWh which is enough to make the trend non-smooth.

Sensitivity parameter :	Collector Controller Sensor Rel. Height [-]	0.050 – 0.500

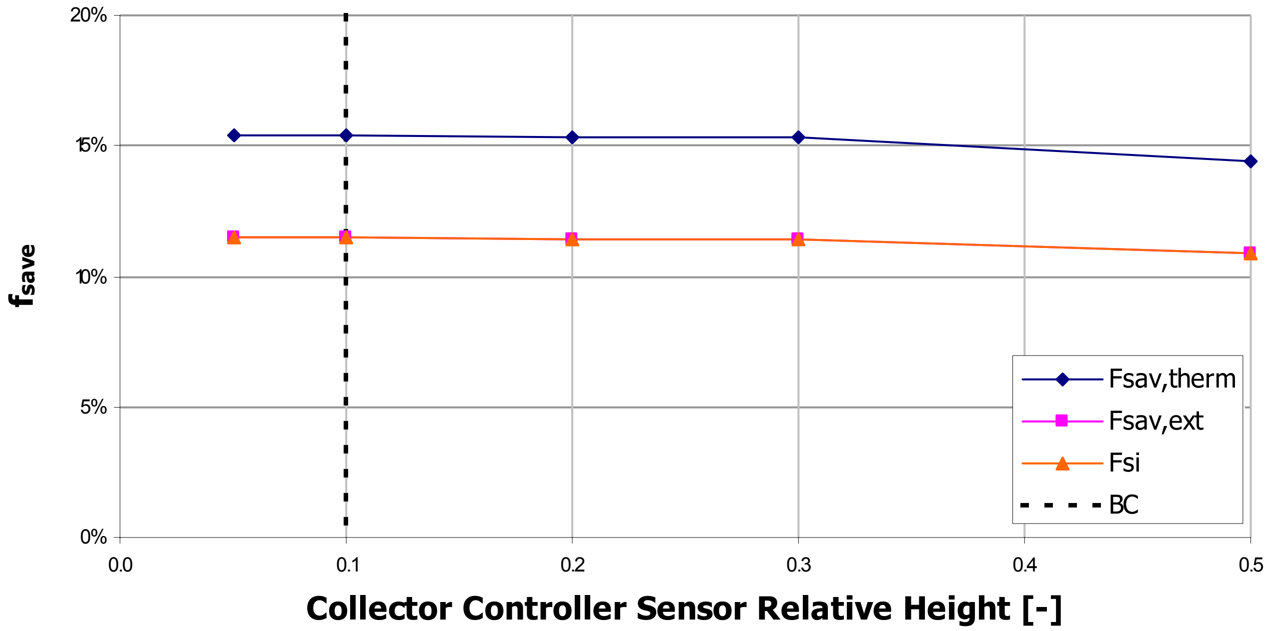


Fig. 27. Variation of fractional energy savings with the collector controller's sensor position.

Differences from Base Case
None

Description of Results
Above a height of approx. 0.3 the savings start to decrease. Below this height there is little influence on the savings from the collector controller's position.

Comments
None.

Sensitivity parameter :	Tube Insulation Thickness [cm]	0.5 – 3.0 cm

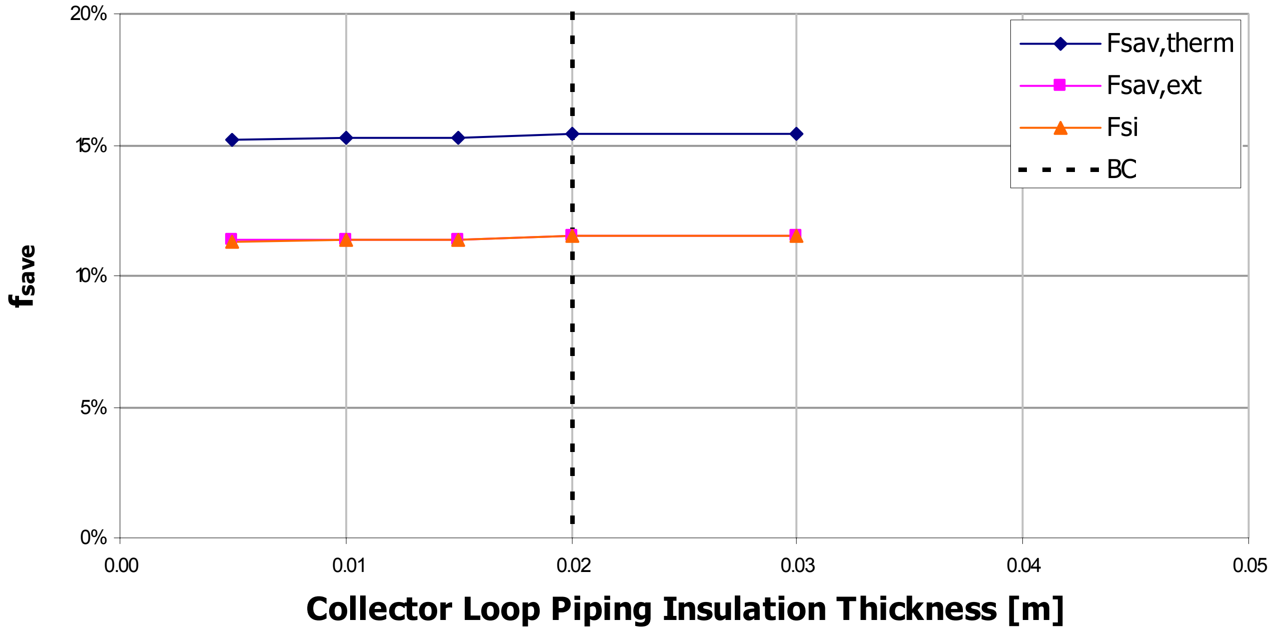


Fig. 28. Variation of fractional energy savings with the insulation thickness round the collector tubing.

Differences from Base Case
None

Description of Results
Here there is a very slight increase in savings with increased insulation thickness. The effect is quite small as the heat loss from the tubes is only 0.9% of the total energy transfer in the system.

Comments
The insulation had a conductivity of 0.04 W/m.K and the collector pipe size was12 mm external diameter. No correction factor for “imperfections” was included.

Sensitivity parameter :	Auxiliary Heater Type (Stockholm climate, 60 kWh/m2.yr house)	-

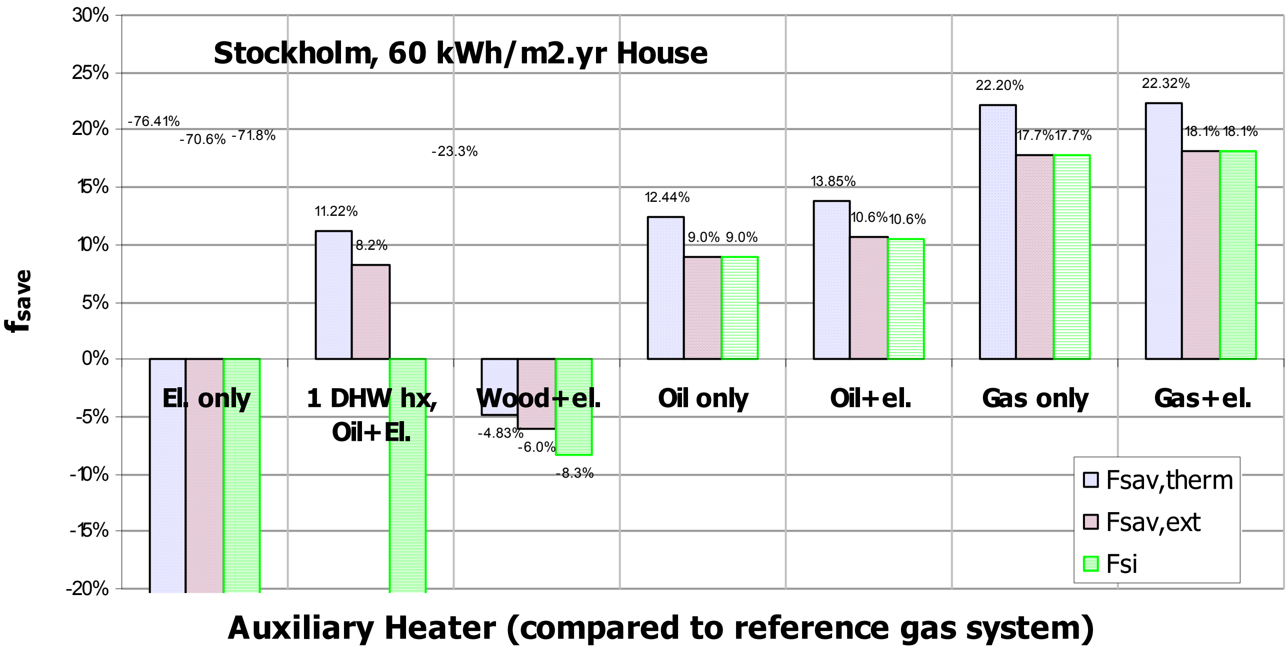


Fig. 29. Variation of fractional energy savings with the type of auxiliary used in the system. All savings are in relation to the reference gas system which has higher efficiencies than all the other auxiliaries.

Differences from Base Case

The Stockholm climate was used instead of Zurich, but the simulations had the same house as in the base case. The same period is used for the boiler shut down for all system variations that have a combination of energy sources. The following summary of the conditions for the other auxiliaries follows (efficiencies include standby losses from the boilers):

- Electricity. Annual efficiency 40%.
- Wood-fuel (manually fired). Annual efficiency for the wood boiler was 73.9%. A simple control algorithm was used which was not optimised for solar applications. A store volume of 1.5 m^3 was used. Large heat losses come from the store.
- Oil. The same boiler model and parameter values as in the base case. Annual efficiency for this load was 80.8% for oil only and 82.6% for oil and electricity.
- Gas. Same model and parameter values as used in the scsth system. Annual efficiency for this load was 90.9% for gas only and 91.7% for gas and electricity. This is higher than that assumed efficiency in the gas reference system which assumed an annual efficiency of 85%.

The system was also simulated using only the upper DHW heat exchanger, a system variation that used to be quite common. In this case the settings for the controllers was the same as for those used with both heat exchangers. The same size heat exchanger was used.

Description of Results

As can be seen there is a very large spread in savings for the different energy sources. Most of this is attributable to the different efficiencies for the sources. All savings are relative to the gas only reference system. Gas has the highest efficiencies of all fuels, although the efficiency assumed for the reference system is lower than that simulated here. The efficiency for electricity affects the values depending on the amount of electricity used. For the electricity only system, a value of 70% instead of the used value of 40% gives the electricity only system a fractional saving of around 0%. To make this comparison more interesting it would be necessary to simulate reference systems with oil, electricity and solid wood-fuel boiler. An interesting result is that for both oil and gas boilers, there is an advantage in turning the boiler off over during the summer and using an electrical heater in the store instead.

The system that uses only one DHW heat exchanger performs worse that the one with two heat exchangers, at least when coupled to an oil boiler. This is due to the fact that the lower part of the store, preferentially heated by solar, takes a long time to cool down in this configuration and the collector has to work at much higher temperatures. The simulation had the same set temperature for store charge, and this was shown to be too low as the penalty value was very high.

Comments

The wood boiler is not a very accurate model. Much more work is required to make the model more realistic. However, even with a realistic model, the system performance is going to be very dependent on the algorithm used for when to charge the store and by how much. Deficiencies in the model can be summed up as:

- All heat in the boiler at the end of a store charge are lost to ambient. Most modern systems allow further discharge of the boiler direct to the heating system after the store is charged.
- Fixed heating rate for the whole combustion cycle and uniform combustion parameters for the whole period.
- Charging could be from 25 kWh to 94 kWh depending on the quantity of heat required as calculated by the control algorithm.

Sensitivity parameter :	Period for Boiler Shutdown / El. Heating (Stockholm climate, 60 kWh/m2.yr house)	0 - 365

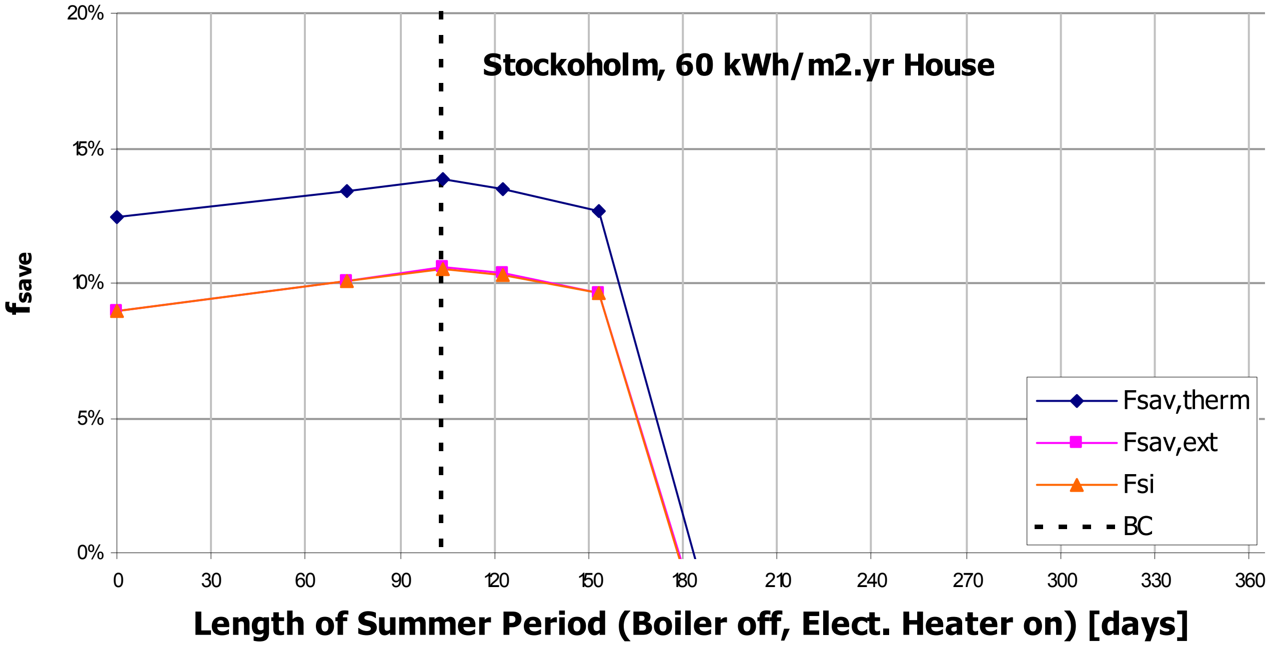


Fig. 30. Variation of fractional energy savings with the period of the year when the oil boiler is switched off and an electrical heater in the store is used as auxiliary instead.

Differences from Base Case
The Stockholm climate was used instead of Zurich, but the simulations had the same house as in the base case. The following dates were used for the electrical heating period.

Days	Start Date	End Date
365	01-jan	31-dec
153	15-apr	15-sep
123	01-maj	01-sep
103	20-maj	01-sep
73	04-jun	16-aug
0	-	-

Description of Results
There is an optimum period for shutting the boiler off and turning the electrical heater on instead. This coincides with the base case which was defined as the uninterrupted period when there was no space heating requirement. This gives the longest period when the boiler is working at a low efficiency (<25% over the summer period).

Comments
None.

4.2 Optimisation of the System

A number of different optimisation runs were carried out with different parameters open and for different conditions regarding base costs and DHW load. These runs were performed in order to get information about the sensitivity of these two important variables. All optimisations were performed for the Stockholm climate and the 60 kWh/m^2.a house. The GenOpt tool was used with the Hooke-Jeeves algorithm. For the optimisation of the system without additional costs, the value of F_{si} was optimised. For the cost optimisations, the value of $Cost_{si}$ was used, where:

$$Cost_{si} = \text{Investment cost} / Q_{si}$$

and Q_{si} is the primary energy savings of the system compared to the reference system less penalties.

A modified penalty function was implemented for DHW penalties as the original equations caused problems for the optimisation algorithm – they were too extreme. The modified penalty equations implemented in TRNSYS were:

MAXPEN = 5*[25,2]*CpWat*(45. - Trfwat)
Qdhwext = GT(45., [25,1]) * [25,2]*CpWat*(45. -[25,1])
Qpenda = [25,2]*CpWat*(((MAX(0,(45.-[25,1]))+1)**4-1))
Qpen45 = MIN(Qpenda, MAXPEN) + Qdhwext

These equations effectively limit the penalty rate to a value that is 5 times the size of the nominal discharge rate.

As the cost functions are only estimates, and in addition change with time, the results for cost optimisations can only be used as guidelines.

Previous work with optimisation and measurement of this system can be seen in (Lorenz *et al.*, 1997; Lorenz *et al.*, 1998; Lorenz *et al.*, 2000; Lorenz, 2001).

4.2.1 Cost Functions

Cost figures are those that were judged representative in Sweden for the system. Several different companies sell the system, each with their own price structure. Cost functions were made for the various components and the insulation. The following are the cost functions that were used based on a currency conversion rate of 9.20 SEK/€:

Collector area: cost_c_area 192 €/m^2
Store volume: cost_Vs 428 €/m^3
Cost store insulation: cost_vins 625 €/m^3 insulation mater.
(standard case has approx. 0.75 m^3 insulation)
Cost for 17 mm diameter heat exchanger tube: cost_hx17 16.3 €/m
Cost for 22 mm diameter heat exchanger tube: cost_hx22 17.4 €/m

The following equations were used to calculate the difference in total cost for the system with respect to the based case system (dC_all) and then finally the total cost of the current system (cost_all).

dhxl_l = 11 * (dhwlUA/6037)
dhxu_l = 11 * (dhwuUA/129.8)
dC_c = (c_area - 10)*cost_c_area
dC_V = (Vs - 0.73)*cost_Vs
dC_i = cost_vins*(V_ins - 4.73*0.12)
dC_chx = 15*cost_hx17*((chxUA/24.57) - 1)
dC_dhx = cost_hx22*(dhxl_l + dhxu_l - 22)
dC_all = dC_c + dC_V + dC_i + dC_chx + dC_dhx
Cost_all = (base_case_cost + dC_all)

4.2.2 Variation of Base Cost and DHW Load Profile

Six optimisation runs are shown here, representing the result of the following table of reference conditions for DHW load and base cost.

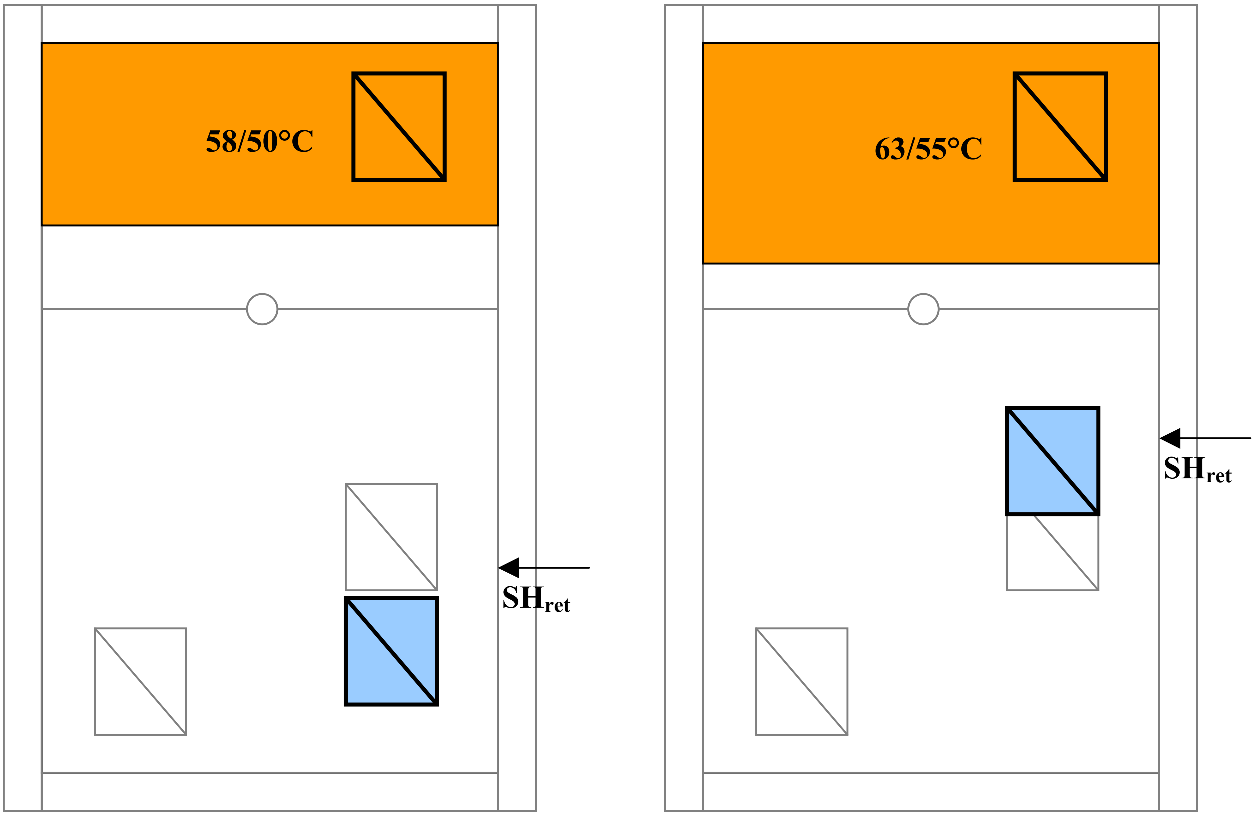
No additional costs	Low-flow DHW load	Task 26 (high-flow) DHW load
Cost Optimisation	Low-flow DHW load Base cost €5 610	Task 26 (high-flow) DHW load Base cost €5 600
Cost Optimisation	Low-flow DHW load Base cost €3 070	Task 26 (high-flow) DHW load Base cost €3 070

The base cost is for the solar heating system and all installation costs for connecting to an existing heating system with oil boiler and radiator heating. The costs of the radiator system and boiler are not included. VAT is also not included. Two different values, extreme ones, were used as the net cost of the solar heating system can be calculated in many ways, depending on what is already existing in the heating system. The lower base cost is for only the solar heating circuit including installation. This assumes that the existing system has a combistore that is already connected to the boiler. The high base cost is for the collector loop and the store and for the reconnecting of the boiler to the new store. The work costs used was €38/hour, and the labour time was estimated based on previous experience.

The low-flow DHW load is a load created by Ulrike Jordan in the same way as the standard Task 26 load, but with no bath loads and the flow restricted to a maximum of 10 l/min. The standard DHW load has maximum flow rates of over 20 l/min.

The following diagrams show the results for the six optimisations in the sensitivity analysis of base cost and DHW load. The base case conditions are shown as grey lines and the solid dark lines show the rough relative size and position of the optimised version. In each case the thermostat setting for the charging of the auxiliary heated part of the store as well as the volume for this was optimised. The three heat exchangers are: collector at lower left, DHW heat exchangers in series (bottom right and top right). The insulation thickness is also shown. To the bottom left of the cost optimisation diagrams the collector size is also shown diagrammatically.

In each case two specific costs ($Cost_{si}$) are given, one for the higher base cost of € 5610 and the other of the lower base cost of € 3070. In addition the improvement in specific cost relative to the base case system for the same DHW load is given as well as the additional investment cost compared to the base case.



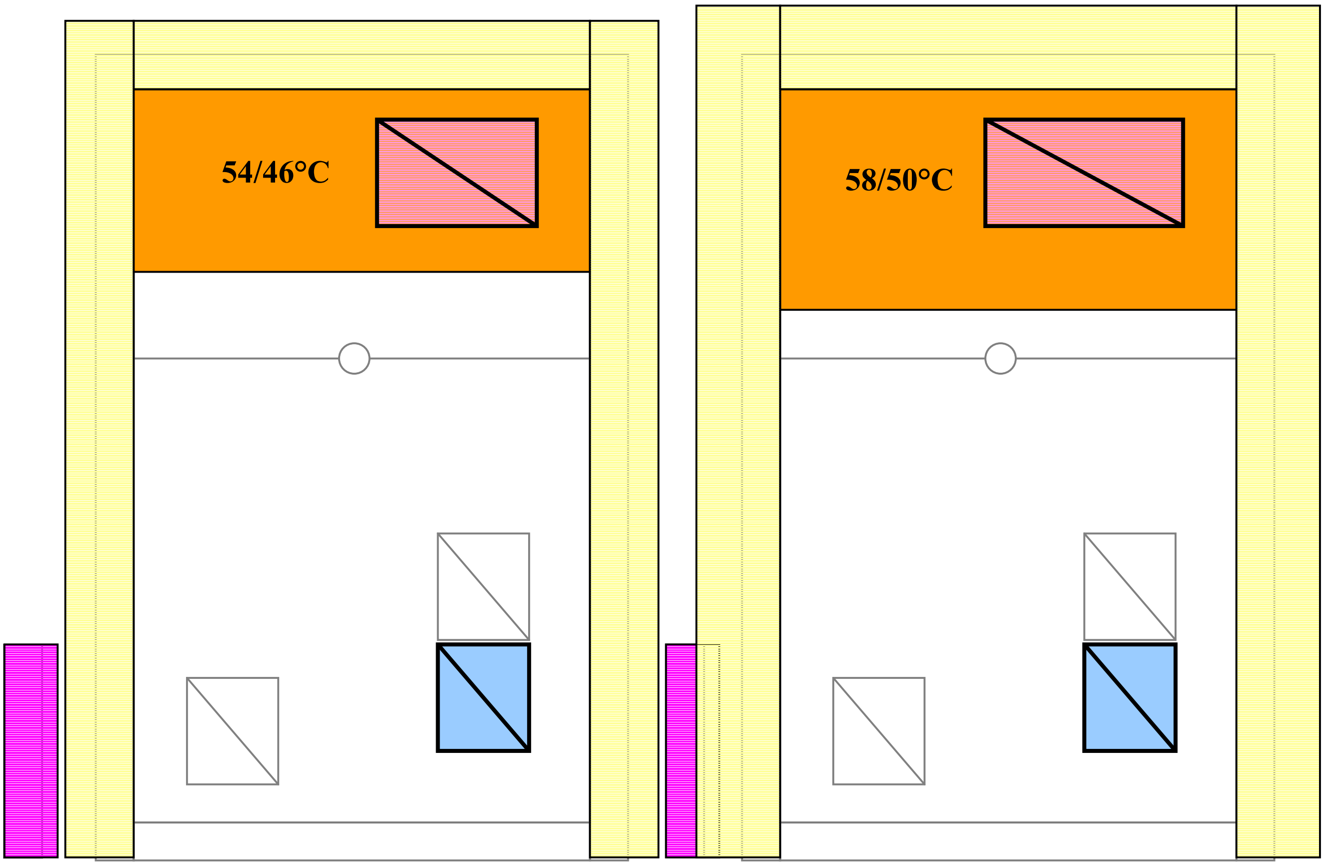
200 Low-Flow DHW
€ 2.04/kWh
€ 1.11/kWh

Solar collector 10 m^2

200 High-Flow DHW
€ 2.38/kWh
€ 1.30/kWh

Fig. 31. Results of optimisation with no additional costs for two different DHW loads. Auxiliary heated volume (orange area), thermostat setting for auxiliary heated area, position of the two DHW heat exchangers and the space heating loop return inlet height were the varied parameters.

Fig. 31 shows that for both low and high-flow DHW loads, a lower thermostat setting and smaller auxiliary volume are possible. For the low-flow DHW load the lower DHW heat exchanger and space heating return inlet should be relatively low, whereas for the high-flow load they should both be higher.

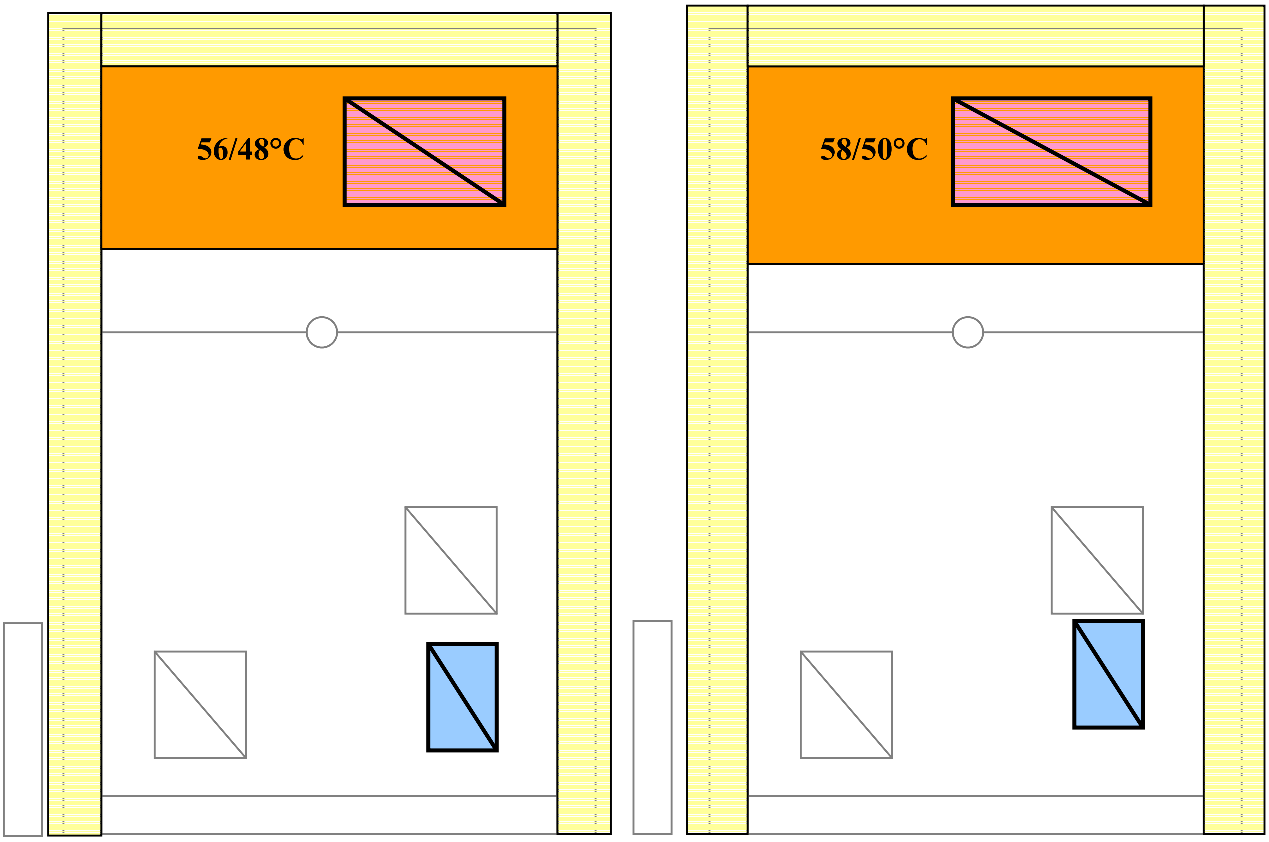


200 Low-Flow DHW
€ 1.92/kWh (-5.5%)
Extra € 1060 investment

200 High-Flow DHW
$ 2.08/kWh (-12.5%)
Extra € 1300 investment

Fig. 32. Results of cost optimisation using the higher base cost of € 5610 for two different DHW loads. Auxiliary heated volume (orange area), thermostat setting for auxiliary heated area, position and size of the two DHW heat exchangers, insulation thickness and the collector area were the varied parameters.

Fig. 32 shows that for cost optimisation with high base costs and both DHW loads, the collector should be 50% larger (15 m^2) and the lower DHW heat exchanger placed at a lower height but same size. The insulation and upper heat exchanger size should be increased significantly for both loads, with the increase being even larger for the high-flow load. The upper DHW heat exchanger should also be significantly larger than for the base case: more than 50% for the low-flow load and nearly 100% for the high-flow load. The required extra investment cost is quite large in both cases (about 20% of base cost), being even more so for the high-flow DHW load.



200 Low-Flow DHW
€ 1.13/kWh (0%)
Extra € 150 investment

200 High-Flow DHW
€ 1.26/kWh (-3.5%)
Extra € 370 investment

Fig. 33. Results of cost optimisation using the lower base cost of € 3070 for two different DHW loads. Auxiliary heated volume (orange area), thermostat setting for auxiliary heated area, position and size of the two DHW heat exchangers, insulation thickness and the collector area were the varied parameters.

Fig. 33 shows that for cost optimisation with low base costs and both loads, the collector should be same size as for the base case and that the lower DHW heat exchanger should be smaller and at a lower height. The insulation and upper heat exchanger size should be increased significantly for both loads, with the increase being even larger for the high-flow load. The upper DHW heat exchanger should also be significantly larger than for the base case: more than 50% for the low-flow load and nearly 100% for the high-flow load. The required extra investment cost is quite small in both cases.

Conclusions for Variation of Base Cost and DHW Load

Auxiliary volume:	This should be smaller than base case in all variations, but should be slightly larger for the high-flow DHW load compared to the low-flow load.
Thermostat setting:	This should be 48/56°C for the low-flow DHW load and 50/58°C for the high-flow DHW load. This is much lower than for the base case due to the larger upper DHW heat exchanger that is identified. For the optimised version without additional costs, these settings need to be approx. 4°C higher than for the cost optimised cases.
Insulation:	This should be thicker in all cases. For high base cost and high-flow load, this increase is larger, with the combination of these two best with a 100% increase in thickness.
Upper DHW heat exchanger:	This should be larger in all cases, with the increase being larger for the high-flow load. This result is based on the assumption that the increase in UA-value is linear with cost.
Lower DHW heat exchanger:	This should be placed lower in all cases, and for the low base cost it should be slightly smaller.
Collector size:	This should be 15 m^2 for the high base cost and the base case value of 10 m^2 for the low base cost.

As a summary, it can be stated that the auxiliary volume should be smaller and the thermostat setting substantially lower, as low as possible. The insulation should be thicker and the upper DHW heat exchanger much larger. If a high base cost is assumed then a larger collector is more cost effective as well as even thicker insulation.

It can also be stated that there are significant differences in the optimised system for the low-flow DHW load compared to that for the standard, high-flow load.

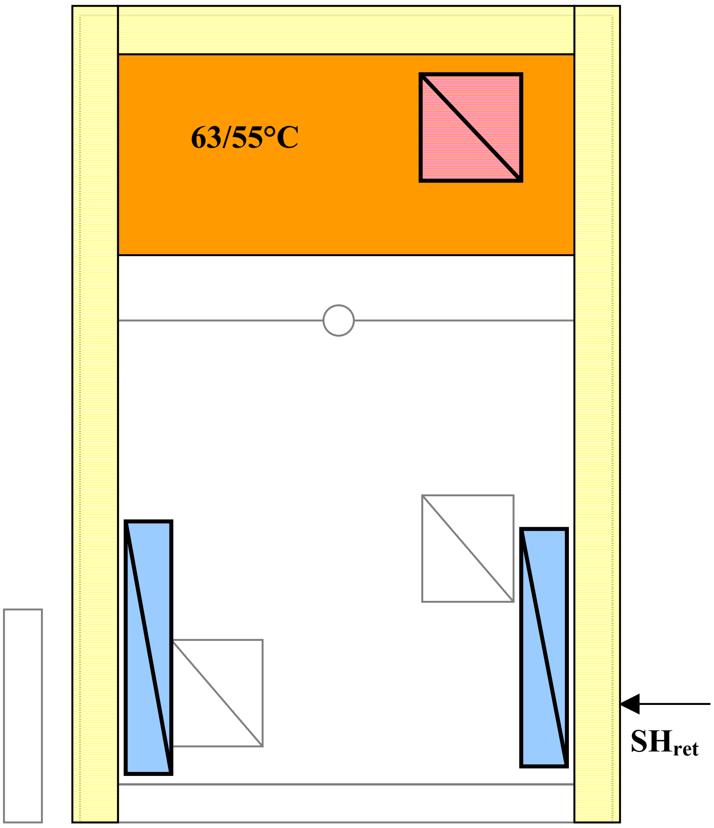
4.3 Definition of Optimised System Without Additional Costs

In addition to the optimisations described above, a final optimisation was performed for the standard high-flow DHW load without additional costs. The vertical extent of the collector and lower DHW heat exchangers was also optimised, but the UA-value was kept constant. For the UA-value to be the same for a stretched heat exchanger, a different diameter would be required as well as a different length.

The optimised system is the same as the base case system defined in section 2.2 except for the following parameters.

Auxiliary volume:	0.17 m^3, equivalent to relative height of 0.73 for the electrical heater and the outlet to the boiler.
Thermostat setting for store charge:	55/63°C.
Boiler set temperature:	70°C.
Upper DHW heat exchanger:	Outlet at 0.97 relative height.
Lower DHW heat exchanger:	Inlet at a relative height of 0.05 and outlet at 0.36.
Collector heat exchanger:	Inlet at 0.40 and outlet at 0.03 relative height. The flow was defined as 60*(1-inlet_height), in this case 36 kg/min.m^2.
Space heating return:	Inlet at 0.16 relative height.

This data is summarised in Fig. 34. In essence, the collector and lower DHW heat exchangers are stretched somewhat compared to base case, and the collector flow is slightly lower. This setup gives nearly 4% relative improvement in performance ($F_{sav,th}$) compared to the other optimisation with no additional costs shown in section 4.2.2 and 17% relative improvement compared to the base case for the given conditions.



200 High-Flow DHW
€ 2.29/kWh (€ 5610 base cost, -3.9%)
€ 1.55/kWh (€ 3800 base cost)

Fig. 34. Results of optimisation with <u>no additional costs</u> for the <u>standard DHW load</u>. Auxiliary heated volume (orange area), thermostat setting for auxiliary heated area, position of the lower DHW heat exchangers, collector heat exchanger and space heating return inlets were the varied parameters.

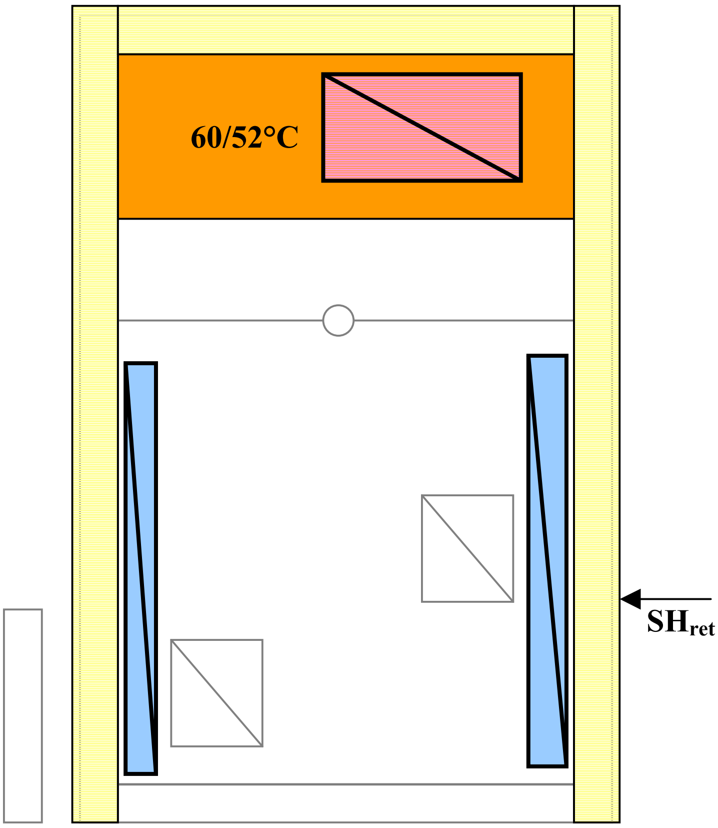
4.4 Definition of Cost Optimised System

In addition to the optimisations described above, a final cost optimisation was performed for the standard high-flow DHW load. In this case a base cost of €3 800 was used, representing the full cost of the system including installation less the cost of a DHW store for a standard system. The vertical extent of the collector and lower DHW heat exchangers was also optimised as well as the size of the store.

The optimised system is the same as the base case system defined in section 2.2 except for the following parameters.

Store size:	Slightly smaller at 0.70 m^3.
Auxiliary volume:	0.14 m^3, equivalent to relative height of 0.77 for the electrical heater and the outlet to the boiler.
Thermostat setting for store charge:	52/60°C.
Boiler set temperature:	70°C.
Upper DHW heat exchanger:	Twice the size as the base case (22 m of 22 mm diameter finned coil tube). Outlet at 0.97 relative height.
Lower DHW heat exchanger:	Inlet at a relative height of 0.05 and outlet at 0.60.
Store insulation:	25% thicker at 16 cm on sides and top, 12 cm for the bottom. This is equivalent to UA-values of 1.84 W/K for the sides, 0.22 W/K for the top and 0.30 W/K for the bottom.
Collector heat exchanger:	Inlet at 0.56 and outlet at 0.03 relative height. The flow was defined as 60*(1-inlet_height), in this case 26.4 kg/min.m^2.
Space heating return:	Inlet at 0.32 relative height.

This data is summarised diagrammatically in Fig. 35. In essence, the collector and lower DHW heat exchangers are stretched significantly compared to base case, and the collector flow is lower. This setup gives nearly 4% relative improvement in specific cost compared to the best optimisation result without allowing additional costs and nearly 30% relative improvement in $F_{sav,th}$ compared to the base case for the given conditions. This is achieved with an extra investment of only €250.



200 High-Flow DHW
€ 1.50/kWh (-3.6% compared to no cost optimised system)
Extra € 250 investment

Fig. 35. Results of cost optimisation using the base cost of € 3800 for the standard DHW load. Auxiliary heated volume (orange area), thermostat setting for auxiliary heated area, position and size of the two DHW heat exchangers, insulation thickness and the collector area, store volume, collector heat exchanger and space heating return inlets were the varied parameters.

5 Analysis using FSC

Fig. 36 shows the FSC characteristic for system 11 for four different cases. The upper solid line is for the cost optimised solution using the standard gas boiler, the lower solid line for the same system except with the standard oil boiler, the dotted line for the optimised system with no additional costs and the dashed line for the base case system. This shows the significant improvements achieved by the optimisation process. It also shows that the system improvement is even greater if a better boiler is used, in this case the standard gas boiler, which has 10% higher annual boiler efficiency than the oil boiler used in the reference non-solar heating system in Zurich.

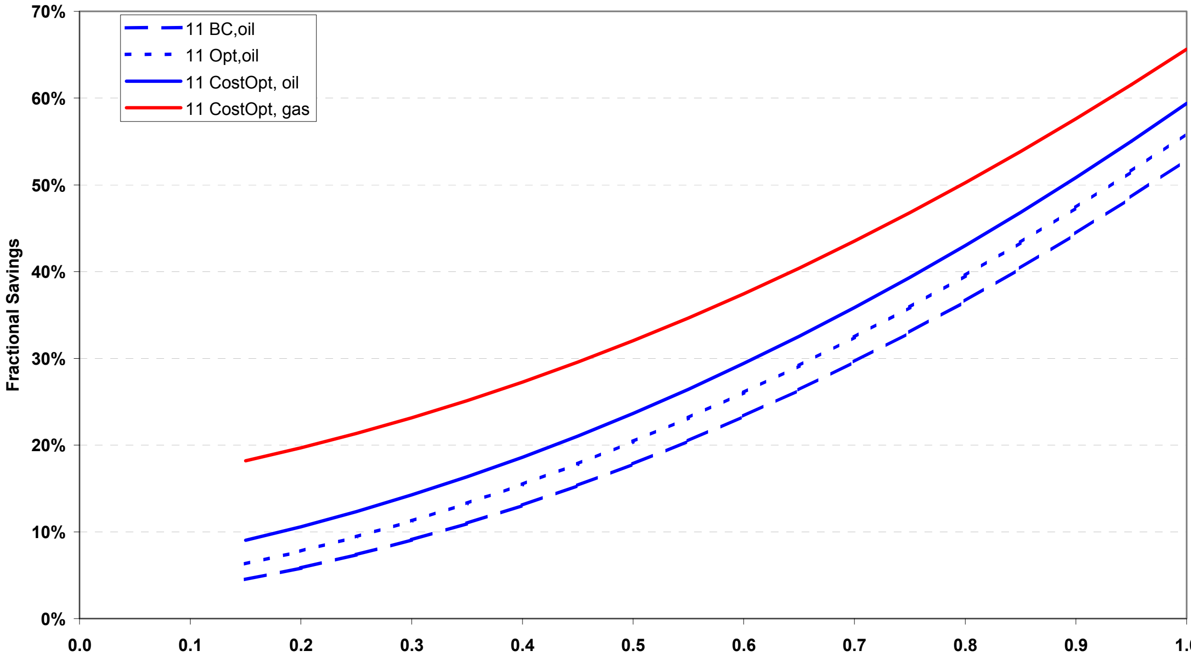


Fig. 36. FSC characteristics for system 11 based on 3 climates (Carpentras, Zurich, Stockholm), 3 loads (30, 60, 100 kWh/m²a single family buildings and three collector sizes (5, 10, 20 m^2).

When the size of the system is altered, then the assumptions regarding placement of heat exchangers is not necessary valid and excessive penalties may occur. This was the case with system 11, at least for the optimised systems where the optimisation was for 10 m^2. Here slight alterations in the auxiliary heated volume and thermostat settings were required to avoid excessive penalties for DHW preparation.

The FSC calculations are based on the following conditions for the base case system:

Collector Size [m^2]	Store Volume [m^3]
5	0.5
10	0.73
20	1.5

For the optimised system with no additional costs the following conditions applied:

Collector Size [m^2]	Store Volume [m^3]	Auxiliary Heated Volume [m^3]	Thermostat Set Temp. [°C]
5	0.5	0.17	70
10	0.73	0.17	70
20	1.5	0.23	67

For the cost optimised system the following conditions applied:

Collector Size [m^2]	Store Volume [m^3]	Auxiliary Heated Volume [m^3]
5	0.5	0.14
10	0.73	0.14
20	1.5	0.20

In addition to the above, the electrical heater was turned on for the hours defined in section 1.1 for the relevant climates and houses. This is in principal for the period without space heating.

6 Lessons learned

The following lessons were learned concerning the simulation of the system

6.1 Energy Balances

The boiler model acts as a single node heat exchanger for heat transfer from the exhaust gases to the water. Oil boilers generally have relatively large volumes and this volume is fairly well mixed, making it behave very differently from a single node heat exchanger. In order to be able to use the model for this type of boiler, a high flow is sent through the boiler using a shunt across the input and output. This shunt is designed so that the inlet temperature is the lower temperature of the hysteresis of the internal thermostat. This means that the average boiler temperature is midway in the hysteresis region. This should approximately be the mean temperature of a real boiler during standby or in continual operation. The original definition of the oil boiler used a shunt made of two valves, a flow diverter and a flow mixer. This configuration worked, but it was soon clear that the energy balance for the boiler was too high. This was due to the fact that the temperature between the inlet and outlet is always fixed to the hysteresis of the controller, in this case 5 K. If the convergence tolerance is 0.001 and the temperature is 70°C, this means that a closure difference (difference for iteration) of 0.07 K can occur, which is 1.4% of the temperature difference and hence heat output. If this closure error is random, then this is not a problem, as the closure errors tend to cancel one another out over a longer time period. If however, as in this case, they are not random, then significant energy balance errors for the loop occur during the year. In this case over 1% annual energy balance errors were found. This is too high. To reduce it, the shunt was incorporated into the boiler model (v3.03 of Type 170).

Lesson 1: It is important to include energy balances for the different loops to check for unforeseen problems.

Lesson 2: Loops with high flows and low dT that operate at reasonably high temperature (>50°C) can give relatively large energy balance errors if the closure error is not semi-random.

6.2 Automatic Optimisation using GenOpt

The optimisations performed for System #11 were carried out using the automatic optimisation program GenOpt. This was found to be simple to use, although it took some time to find a suitable algorithm and settings for it. No detailed search and study of algorithms was carried out. For this see (Krause *et al.*, 2002). Optimisations with up to 10 parameters were performed, although with this number of parameters it was not so clear that the global optimum was achieved.

The target function for optimisation was either F_{si} or a specific cost that was also dependent on the penalties. The penalties for DHW, when optimising the auxiliary heated volume and temperature, vary semi-randomly due to the random nature of the charging of the store due to the hysteresis of the controller. The original penalty function for DHW gave too large a penalty and penalties for a single discharge could dominate the total for the whole year and even be highly significant for the optimisation algorithm. The penalty function was thus modified to give a limited penalty for each time step that was five times the nominal energy to be discharged for that time step.

6.3 DHW Load Profiles

During the course of the Task work, the definition of the DHW load profile was changed. Both profiles were for a time step of 0.1 hour. The original was created from a profile with a smaller time step and the increase in time step led to slightly smaller maximum flows than the final version that was created directly by the load profile generator program. As a comparison, the original profile had a maximum flow rate of 1062 kg/hr with the next highest being 1002 kg/hr. The final version had 7 time steps with flows greater than 1200 kg/hr with the greatest being 1332 kg/hr. These differences made significant differences to the DHW penalties for system 11, that uses load side heat exchangers for preparing DHW.

It should be noted that the DHW profile chosen for Task 26 is relatively extreme as many installations do not have to provide flows above 1000 kg/hr. This means that all systems simulated in the Task provide very good thermal comfort.

6.4 Control of Store Charging

In this model the store is charged from the boiler under the control of an on/off controller with hysteresis. The single sensor for this controller is located just above the outlet from the store to the boiler. During periods of high heating load, there is a sharp boundary layer between the hot water heated by the auxiliary, and the cooler water returned from the heating loop. This boundary layer moves up and down relatively quickly resulting in very fast changes in temperature at the controller's sensor. This has the consequence that the controller cannot decide whether it should be on or off for the time step and is thus "stuck". The standard solutions to this problem in simulations are to either decrease the time step or increase the deadband (hysteresis) of the controller. An alternative would be to introduce a two sensor controller with the upper sensor for starting and the lower for stopping.

6.5 Boiler Shutdown During Summer

Both the gas boiler and the oil boilers defined within Task 26 have very low efficiency during the summer in the solar heating systems. This is due to the very low requirement of heat from the boiler to the system. In System 11 the boiler is usually shut down during the summer and auxiliary heat is provided by an electrical heater in the store. The sensitivity analysis showed that for system 11 (oil boiler) with the Stockholm climate, the optimum period for this shutdown period was for the interval when no space heating was required. This optimum period is likely to be dependent on: the absolute level of solar fraction, the climate and the efficiency of the boiler. However, under the same conditions it was also shown that less primary energy was used even if the system used a gas boiler that was turned off during the summer.

6.6 Convergence Problems with Space Heating System

The space heating system loop, with the dynamic radiator, PID controller, store and house had difficulty in converging quite often. In a separate work, this was solved by adding a time delay to the temperature passed to the PID controller. This is roughly equivalent to a time constant for the thermostat sensor, and is of the same order of magnitude as in reality (for the simulations done here).

7 References

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Streicher, W., Heimrath, R., Structure of the Reference Buildings of Task 26, Technical Report, IEA SHC Task 26 Solar Combisystems, ***http://www.iea-shc.org***, 2003

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Appendix 1 Description of Components Specific to This System

1.1 Switch Between Winter and Summer Seasons for System #11

Time Dependent Forcing Function

Function: Switch between boiler (winter) and electrical heater (summer) and pump to heating system. The boiler is off during summer. Start/End times were identified after studying the heating loads

	Winter Season	
	End (hr)	**Start (hr)**
Carpentras 100kWh	3296	6584
Zurich 100kWh	3488	6451
Stockholm 100kWh	3391	5741
Carpentras 60kWh	3274	7199
Zurich 60kWh	3348	6509
Stockholm 60kWh	3369	5851
Carpentras 30kWh	2146	7231
Zurich 30kWh	3295	6584
Stockholm 30kWh	3345	6074

Outputs : 0 for winter season, 1 for summer

Appendix 2 Parameters identified for the Store Model Using prEN 12977-3.

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2.1 General Parameters

Height:	1.58m	{fixed}
Heat Loss Coefficient: CEN	UA_{s1} = 1.44 W/K (5.20 kJ/h.K)	{fit}
	UA_{bot} = 0.59 W/K (2.22 kJ/h.K)	{fit}
Effective Vertical Conduction:	1.32 W/m.K (4.75 W/h.m.K)	{fit}
Number of nodes	100	{fixed}
Water Volume	729 liter	{fit}
	(+ 8 liter antifreeze in ext. solar heat exchanger and 5 liter in DHW heat exch.)	

2.2 Collector Loop

Heat Exchanger		
Volume	8 liter antifreeze	{fixed}
Inlet (geometric height)	0.2 [relative height]	{fixed}
Outlet	0.036 [relative height]	{fit}
Heat Transfer Coefficient (UA)	UAh1 = 24.6 kJ/h.K	{fit}
	b_{h1}=0.0, b_{h2}=0.0,	{fixed}
	b_{h3}=1.163	{fit}
	This gives a UA-value at T_m=40°C and flow of 120 l/h:	
	$UA_{40,120}$ = 499 W/K (1796 kJ/h.K)	
Option for Stratified Charging	Off	

2.3 Electrical Auxiliary

This was modelled using the auxiliary heater as part of type 140.

Auxiliary power	3.0 kW (10800 kJ/h)	{fixed}
Electrical heater position	0.673 [relative height]	{fit}
Sensor position	0.692 [relative height]	{fit}
Set temperature of thermostat	56.4°C	{fit}
Deadband of thermostat	7.7°C	{fit}

2.4 Boiler Connection

This was modelled as a simple inlet/outlet double port.

Inlet	0.949 [relative height]	{fit}
Outlet	0.686 [relative height]	{fit}
Option for Stratified Charging	Off	

2.5 Heating System Connection

This was modelled as a double port.

Inlet (could not be identified)	0.0 [relative height]	{fixed}
Outlet	0.915 [relative height]	{fit}
Option for Stratified Charging	Off	

2.6 Hot Water Preparation

This was modelled using two load side heat exchangers within Type 140. The model used measured data as input for both heat exchangers i.e. for the upper heat exchanger the inlet temperature was the one measured at the outlet of the lower heat exchanger.

Lower Heat Exchanger		
Inlet (geometric height)	0.20 [relative height]	{fixed}
Outlet	0.46 [relative height]	{fit}
Heat Transfer Coefficient (UA)	UAh1 = 6037 kJ/h.K	{fit}
	b_{h12}=0.0,	{fixed}
	b_{h11}=0.3086, b_{h13}=5.64E-5	{fit}
	This gives a UA-value at T_m=40°C and flow of 600 l/h: $UA_{40,600}$ = 965 W/K (3473 kJ/h.K)	
Option for Stratified Charging	Off	
Upper Heat Exchanger		
Inlet (geometric height)	0.73 [relative height]	{fixed}
Outlet	0.879 [relative height]	{fit}
Heat Transfer Coefficient (UA)	UAh1 = 129.8 kJ/h.K	{fit}
	b_{h12}=0.0,	{fixed}
	b_{h11}=0.0874, b_{h13}=0.9965	{fit}
	This gives a UA-value at T_m=40°C and flow of 600 l/h: $UA_{40,600}$ = 1217 W/K (4382 kJ/h.K)	
Option for Stratified Charging	Off	

2.7 Temperature Sensors

Measured heights.

2.8 Verification Results

The following is a summary of the results from the verification sequence which comprised 3 days of realistic conditions and a fourth day of standby. The actual measured energy values have been corrected for the sensor response time by the following amounts. No correction can be applied to the power differences:

Upper DHW	0.52 kWh more than measured
Lower DHW	the same as measured
Boiler	0.40 kWH more than measured

Simulation using the measured electrical auxiliary data as input.

	Heating	Collector	Final	DHW	Boiler

	System	Loop	Disch.	Lower	Upper	Port
	kWh	kWh	kWh	kWh	kWh	kWh
Energy Totals- meas	-83.2	34.2	-17.9	-8.23	-10.72	74.9
Energy Totals-sim	-84.9	36.1	-17.3	-9.06	-11.10	74.6
Differences between measured and simulated according to CEN.						
Energy Difference	3.0%	4.1%	-3.4%	10.3%	4.5%	-0.4%
Mean Power Diff.	3.1%	5.2%	7.0%	13.6%	17.1%	5.3%

Simulating the electrical auxiliary element.

	Heating	Collector	Electr.	DHWBoiler		
	System	Loop	Aux.	Lower	Upper	Port
	kWh	kWh	kWh	kWh	kWh	kWh
Energy Totals- meas	-83.2	34.2	17.20	-8.23	-10.72	74.9
Energy Totals-sim	-74.2	36.1	15.40	-9.06	-11.10	74.9
Differences between measured and simulated according to CEN.						
Energy Difference	2.0%	5.6%	-10.5%	10.1%	3.5%	0.0%
Mean Power Diff.	3.0%	5.7%		13.8%	14.6%	5.1%

2.8.1 Comments

The results of the verification are not very good with respect to the load side heat exchangers for DHW preparation and electrical auxiliary. Even the solar heat exchanger is outside limits proposed by the CEN standard, but this could be the result of the inaccuracies for the load side heat exchangers. The basic equation in the model may be not adequate for this type of usage (DHW preparation), or that the measurement data is not adequate.

The auxiliary inaccuracy is due to plume entrainment during high solar heat transfer rates leading to mixing near the boundary between hot and cold created by the auxiliary.

2.9 Schematic of Tank as Tested