Report on Solar Combisystems Modelled in Task 26

Appendix 7:
Generic System #12: Space Heating Store with DHW Load Side Heat Exchanger(s) and External Auxiliary Boiler (Advanced Version)

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 7:
Generic System #12: Space Heating Store with DHW Load Side Heat Exchanger(s) and External Auxiliary Boiler (Advanced Version)

by

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A technical report of Subtask C

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Contents

SUMMARY

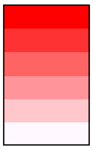
System #12 is an advanced version of System #11 using an extra heat exchanger in the collector loop and a four-way valve with two outlets from the store for connection to the space-heating loop. The collector flow goes either through the upper heat exchanger or through the lower one, using high flow. The manufacturer of this system in Sweden also uses an advanced controller for switching between the two heat exchangers and for varying the flow in the circuit during marginal conditions. This controller was modelled in detail but not validated against the real controller. It is designed to maximise solar contribution during varying radiation conditions.

The results show that the base case configuration, as sold by the manufacturer in Sweden, is not designed for such high hot water flow rates and discharges as exist in the standard task 26 load profile. Modifications were necessary in the model to be able to meet this profile. The optimisation of the system was based on the results of the cost optimised System #11, principally the use of a larger upper DHW heat exchanger. For a modern house in Stockholm with 10 m^2 collector it is better to use high flow in the collector loop, using either the upper or the lower heat exchanger rather than to use low flow, using either the lower or both heat exchangers.

The optimised System #12 performs significantly better than the optimised System #11. The main difference between the systems are the extra collector heat exchanger, the advanced controller and the use of a four-way valve for supply to the space-heating circuit. The four-way valve provides the most significant improvement. The extra heat exchanger gives marginal improvement for a normally dimensioned store but gives a significant improvement for larger than normal stores. This is the case for 10 m^2 collector and 1.5 m^3 store, a configuration common in Sweden when the system is connected to a solid wood fired boiler. No determination of the benefit of the advanced control method using flow variation in the collector loop was possible, as hourly weather data was used in all cases. It is thus possible that using weather data with shorter time steps, this system would perform even better compared to System #11, which uses a simpler controller.

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

Sweden



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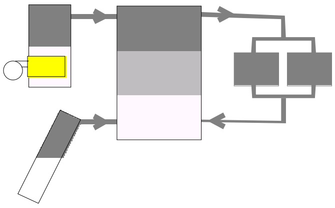
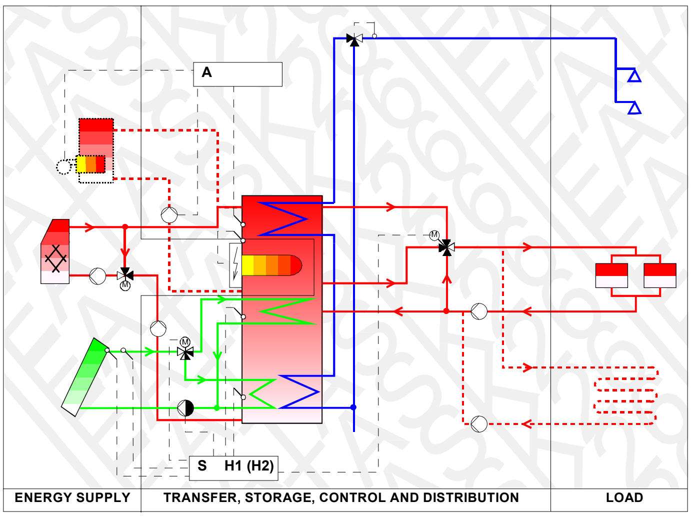


Main features

This system is very similar to the previous system but with more sophistication in the collector loop, in the space-heating loop and in the controller. Two immersed heat exchangers are connected to the collector loop to increase the thermal stratification in the storage tank.

Heat management philosophy

The collector loop pump is turned on under control of the absorber plate temperature. The speed of this pump is then controlled by the temperature difference between the collector outlet and either the temperature of the top or bottom tank sensor, depending upon whether the domestic-hot-water section or space heating section of the tank is to be heated. The space-heating loop is connected to the tank with a 4-way valve enabling heat delivery from the central part of the tank.



The electric heater is under control of a separate thermostat, but is locked out by the solar controller when the collector loop pump is running.

Monitoring capabilities and the ability to compute energy balances are included in the controller, which can be easily connected to a PC.

Specific aspects, influence of the auxiliary energy source on system design and dimensioning are identical to the previous system.

Cost (range)

A typical system with 10 m^2 of solar collectors and a 1 500 litre storage tank with a wood boiler as auxiliary costs about 13 300 EUR. A similar reference system without solar heating costs about 8 600 EUR.

Market distribution

This system has been marketed by one company in Sweden since 1993. This company installed about 2 000 m^2 of solar collectors. The combitank and controller are generally produced by separate companies.

2 Modelling of the system

2.1 *TRNSYS model*

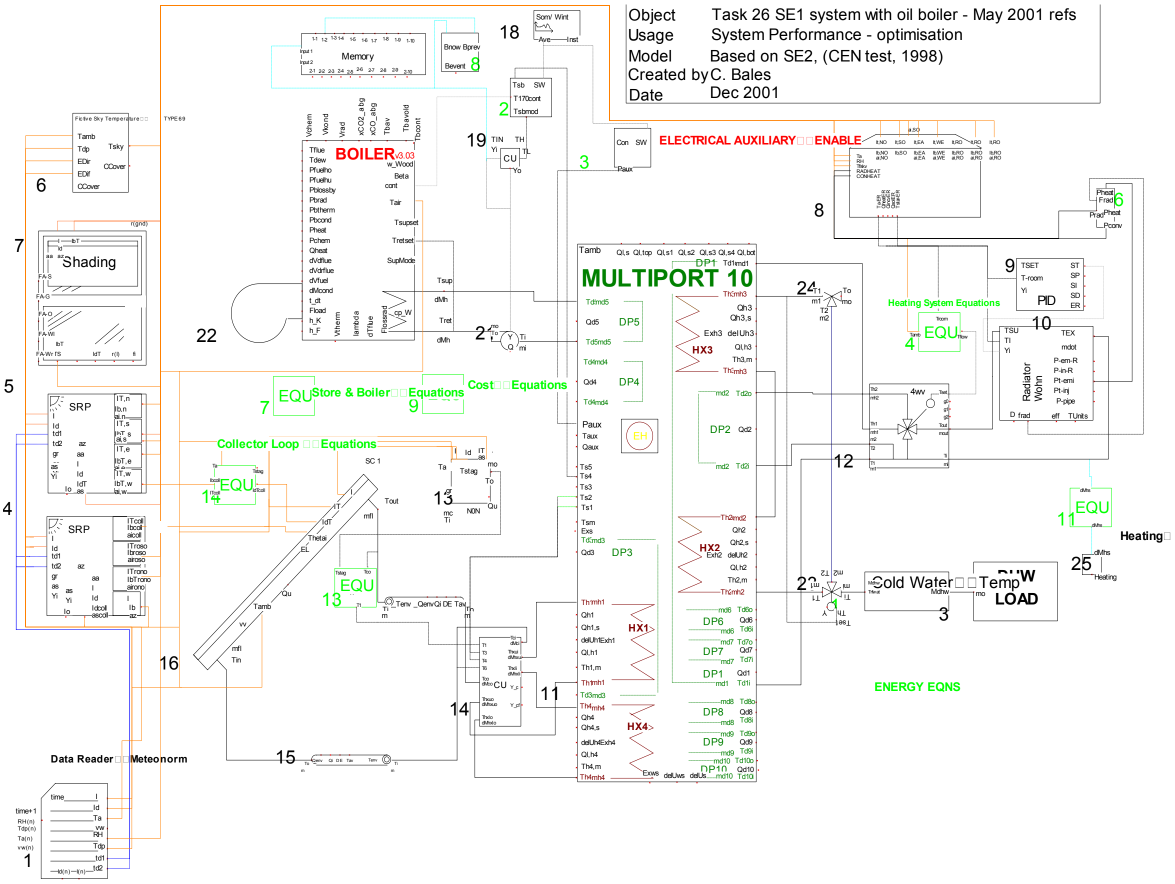


Fig. 1. Modelling of System #12 in PRESIM/TRNSYS. The black numbers are the unit numbers and the green ones the order of the equations sets.

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.

2.2.1 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)

2.2.2 Pipes between Collector and Storage:

Type 31 (16 & 18)	Outer diameter	0.015 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)

2.2.3 Store

Type 140 v1.98 (11). The majority of parameter values used here were those identified using prEN12977-3 for the store of System #11 in May 1999. The ones that differ are the heat loss coefficients and an extra heat exchanger for the solar circuit. This heat exchanger was assumed to have the same UA-value as the other collector heat exchanger, as it has the same dimensions. The inlet and outlet heights also differ somewhat between Systems #11 and #12. The store has been designed for a smaller DHW load than used in Task 26, especially in terms of maximum flow rate and discharge energy. Simulations of the manufacturers design gave large penalty values. *In the base case simulation model some of the inlets and outlets were moved to give a larger auxiliary heated volume, and thus reduced DHW penalties.* The values that have been changed with respect to the manufacturers standard design have the manufacturer's values in brackets. The heights given here are as relative heights as used in type 140. They were calculated using the geometry of the store.

Heat Losses

UA-value for sides [W/K] = (0.04/dinmzo)*UAlscorr*2*$(Vs*Hs*\pi)^{0.5}$ = 1.67 [W/K]
UA-value for top [W/K]= (0.04/dinmto)*UAlscorr*(Vs/Hs) = 0.19 [W/K]
UA-value for bottom [W/K] = (0.04/dinmbo)*UAlscorr*(Vs/Hs) = 0.19 [W/K]
Where:
UAlscorr = Correction term: UA-value/theor. UA = MAX(1.3, (2.0-Vs/10)) (= 1.93)
Vs = store volume (0.74) [m^3]
Hs = store height (1.64) [m]
dinmzo = insulation thickness for sides (0.18) [m]
dinmto = insulation thickness for top (0.18) [m]
dinmbo = insulation thickness for bottom (0.18) [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.

Height for outlet of upper DHW heat exchanger = 0.99
Height for boiler outlet/electrical auxiliary (zobo) = 1 – (AuxVol/Vs) – 0.01
= 0.774 (0.866 for manufactured)
Height for boiler inlet = 1.00
Where:
AuxVol is the auxiliary heated volume 0.16 m^3 (0.092 for manufactured system)

Positions of Sensors for Controllers

The heights for the temperature sensors were not identified. These were set to the following (heights are relative heights with 1 for the top, 0 for the bottom):

Height for lower collector sensor = 0.00 above the outlet
Height for upper collector sensor = 0.10 above the outlet
Height for boiler controller = outlet height + 0.06 = 0.834
Height for electrical heater thermostat = heater's height + 0.02 = 0.794

2.2.4 Burner (Auxiliary Heating)

Type 170 (22) – Specific Type, data defined by Bales (in agreement with Task 26) for standard oil burner. The burner is controlled using an external on/off controller (20) and uses a shunt to give more realistic properties for the burner. Version 3.03 of this type was used.

Aux. Burner	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

2.2.5 Building

Type56, (Streicher, Heimrath, 2002)

2.2.6 Heat distribution

Type 162 (Data defined in (Weiss, 2003))

2.2.7 Control strategy

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

Controller 1: 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 2: Type 2 as simple on/off controller

Functions : Store Charge Controller

Udb=8 K Ldb=0 K

Turn off (upper) temperature=70°C

Tupi= $T_{store(0.834)}$

Controller 3: type 145, specially developed controller model (See Appendix)

2.3 Validation of the System Model

The system has not been validated as a whole system. The parameter values for the heat exchangers are assumed to be the same as those for System #11. These values were validated against measured data for System #11. The controller has not been validated.

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 #12 is that a later version of the boiler model type 170 that included some bug fixes as well as some changes to the operation as oil boiler. Version 1.98 of type 140 was used instead of version 1.95 as this had four heat exchangers available instead of the standard 3. The same DLL was used for Systems #11 and #12.

#19, scsth	$F_{sav,th}$	$F_{Ssav,ext}$	FSI	Q_{boiler}	Q_{pen} SHLow	Q_{pen} SHUp	Q_{pen} 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	$F_{sav,th}$	$F_{Ssav,ext}$	FSI	Q_{boiler}	Q_{pen} SHLow	Q_{pen} SHUp	Q_{pen} 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

The procedure for choosing the conditions was as follows:

- Simulate the system for the tightest tolerance (0.001), shortest time step (1/40) and 100 store nodes. This was defined as the reference simulation (light grey row).
- 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% (dark grey row).

The lighter grey row is the reference for the comparison, and the darker grey the chosen values for the sensitivity analysis. Thus convergence tolerance of 0.001, time step of 1/20 and 50 store nodes were chosen.

Convergence Tolerance	**Time step**	**Simulation runs**	**Store Nodes**	**Fsav,therm**	**e**
0.001	1/20	Yes	20	16.08%	0.021
0.001	1/20	Yes	50	16.27%	0.009
0.001	1/20	Yes	100	16.18%	0.014
0.001	1/40	Yes	20	16.14%	0.017
0.001	1/40	Yes	50	16.55%	-0.008
0.001	1/40	Yes	100	16.43%	0.000
0.005	1/20	Yes	20	15.79%	0.038
0.005	1/20	Yes	50	16.00%	0.026
0.005	1/20	Yes	100	15.79%	0.038
0.005	1/40	Yes	20	15.91%	0.031
0.005	1/40	Yes	50	16.28%	0.009
0.005	1/40	Yes	100	16.02%	0.024
0.01	1/20	Yes	20	15.53%	0.054
0.01	1/20	Yes	50	15.71%	0.043
0.01	1/20	Yes	100	15.54%	0.054
0.01	1/40	Yes	20	15.56%	0.052
0.01	1/40	Yes	50	16.08%	0.021
0.01	1/40	Yes	100	15.81%	0.037

4 Sensitivity Analysis and Optimisation

4.1 Sensitivity Analysis of the Base Case

The Sensitivity Analysis shown here is for the **Base Case Simulation** model and not the optimised system or manufacturer's. The trends are likely to be very similar in most cases, but the absolute levels will be different.

Main parameters :			
Building :	*SFH60*	Storage Volume :	*0.74* m^3
Climate :	*Zurich*	Auxiliary Volume	*0.16* m^3
Collectors area :	*10.58* m^2	Storage height	*1.64 m*
Outlet/Inlet relative Height of upper DHW heat exchanger	*0.99/0.93*	Outlet/Inlet relative Height of lower DHW heat exchanger	*0.41/0.25*
Outlet/Inlet relative Height of upper collector heat exchanger	*0.62/0.75*	Outlet/Inlet relative Height of Lower collector heat exchanger	*0.07/0.23*
Collector type :	*T26 collector*	Rel. height of oil boiler outlet and electrical heater	*0.774*
Rel. height of oil boiler inlet	*0.10*	Lower Rel. height of heating system outlet	*0.58*
Rel. height of heating system inlet	*0.50*	Upper Rel. height of heating system outlet	*0.90*
Specific flow rate (Collector)	*50 kg/*m^2*h*	Thermal insulation, store (top, bottom & sides)	*18 cm*
Collector azimuth/tilt angle	*0 / 45°*	Nominal aux. heating rate: Oil boiler Elect. Heater in store	 *15 kW* *6 kW*
[1]Lower 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*
[1]Upper Collector heat exchanger UA-value at typical operating conditions	*500 W/k*	[1]Upper DHW heat exch. UA-value at typical operating conditions	*1500 W/K*
Collector tubing & insulation	*15 mm O/D* *20 mm*	Store charge controller El. heater thermostat	*68°C – 75°C* *63°C – 70°C*
Store charge flow rate	*600 kg/h*		
Simulation parameters:		Storage nodes	*50*
Time step	*1/20 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 $f_{sav,therm}$**
Base Case	**-**	**16.27%**
Collector size [m^2] (fixed store size (0.74 m^3)	5 – 30 m^2	9.05 – 27.03%
Collector Size [m2] (fixed store spec. vol. 0.074 m^3/m^2)	5 – 30 m^2	6.22 – 33.31%
Store Size [m3] (fixed collector area of 10.58 m^2)	0.3 – 3.0 m^3	11.77 – 19.12%
Collector Azimuth [°] (fixed tilt of 45°)	-90° - 90°	10.20– 9.61%
Collector Tilt [°] (fixed azimuth of 0°)	15° - 90°	13.94 – 8.81%
[2]Climate (60 kWh SFH)	Carp. / Zur. / Stock.	38.72% /16.27 % / 13.72%
[2]Building (Zurich Climate)	30 / 60 / 100	11.98% / 16.27% / 22.30%
Upper Collector Heat Exchanger Outlet Rel. Height [-]	0.30-0.75	17.80 – 17.88%
Lower Collector Heat Exchanger Outlet Rel. Height [-]	0.05-0.295	16.34 – 15.67%
Lower DHW Heat Exchanger Inlet Rel. Height [-]	0.05- 0.256	16.50 – 16.25%
[3]Upper DHW Heat Exchanger Outlet Rel. Height [-]	0.78 – 1.000	21.15 – 16.27%
[3]Boiler Inlet Rel. Height [-]	0.51 – 1	15.33 – 16.27%
[3]Boiler Outlet & Electrical Heater Rel. Height [-]	0.533-0.877	12.40 – 17.03%
Auxiliary Heated Volume [m3]	0.14 – 0.35	16.54 – 12.13 %
[3]Heating System Inlet Rel. Height [-]	0.1 – 0.550	15.65 – 16.34%
[3]Lower Heating System Outlet Rel. Height [-]	0.483-0.827	16.20 – 15.27%
[3]Upper Heating System Outlet Rel. Height [-]	0.72 – 1.000	16.27 – 16.13%
Lower Collector Heat Exchanger UA (variation from identified value)	-50% - +100%	15.87 – 16.60%
Upper Collector Heat Exchanger UA (variation from identified value)	-50% - +100%	16.06 – 16.40%
[3]Lower DHW Heat Exch. UA (variation from identified value)	-50% - +100%	16.06 – 16.43%
[3]Upper DHW Heat Exch. UA (variation from identified value)	-50% - +100%	17.33 – 16.10%
[4]Store Insulation: top [cm]	4 – 18 cm	13.87 – 16.27%
[4]Store Insulation: sides [cm]	4 – 18 cm	6.21 – 16.27%
[4]Store Insulation: bottom [cm]	4 – 18 cm	16.02 – 16.27%
[4]Store Insulation: whole store [cm]	4 – 18 cm	2.92 – 16.27%

[5]Store Charge/Electrical Heater Thermostat (off) [C]	68 - 75°C	21.35 – 14.04%
Store Charge Controller Sensor Rel. Height [-]	0.0 – 0.12	16.08 – 16.70%
Lower Collector Controller Sensor Rel. Height [-]	0.0 – 0.25	16.27 – 16.27%
Upper Collector Controller Sensor Rel. Height [-]	0.0 – 0.25	15.50 – 17.81%
[6]Tube Insulation Thickness [cm]	0.5 – 3.0 cm	16.10 – 16.36%

[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] All simulation had the oil boiler switched off for the same length of time during summer.

[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 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.

[6] The insulation has a conductivity of 0.04 W/m.K and the collector pipe size was 15 mm external diameter. No correction factor for "imperfections" was included.

Presentation of Results

The results are presented with a page for each of the parameters described in the summary above. Each has a diagram where the values for the three fractional savings indicators are 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 relative to the Task 26 reference system, which assumes an annual efficiency (including standby losses of the boiler) of 85% for the boiler. The oil boiler model used here has an average annual efficiency of approx. 80%.

For nearly all diagrams, the value of Fsi is lower than Fsav,ext. This indicates penalties due to the hot water load not being fully met and suggests that the base case should be slightly resized to provide full hot water comfort. The optimised system design does not have these penalties.

Sensitivity parameter :	Collector size [m^2] (fixed store size 0.74 m^3)	5 – 30 m^2

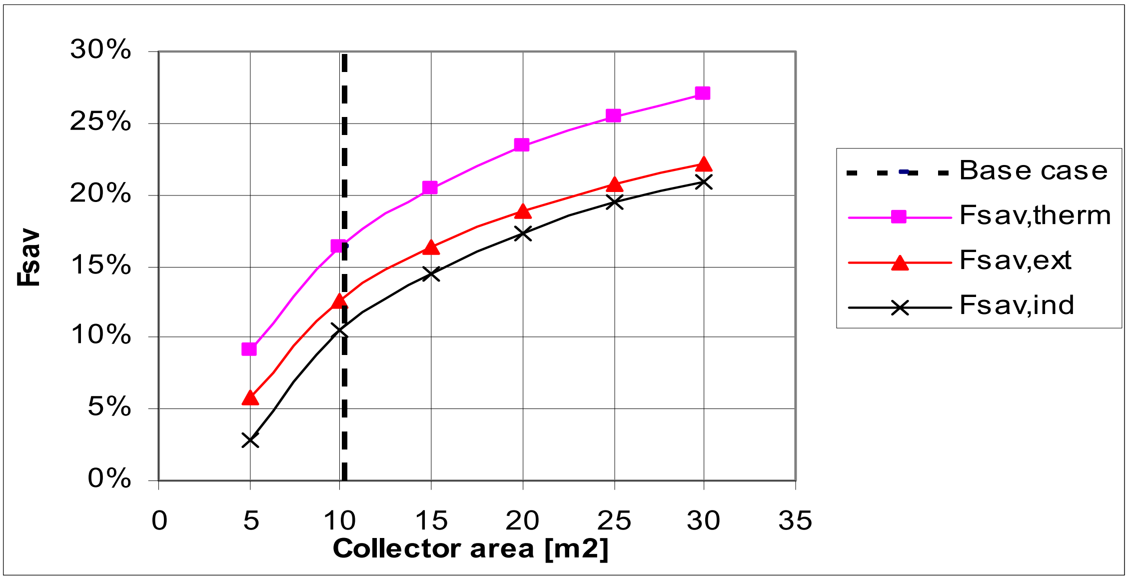


Fig. 2. Variation of fractional energy savings with collector size with fixed store volume of 0.74 m^3.

Differences from Base Case
None

Description of Results
The fractional energy savings increase as expected with increasing collector area.

Comments
None.

Sensitivity parameter :	Collector Size [m2] (fixed store spec. vol. 0.074 m^3/m^2)	5 – 30 m^2

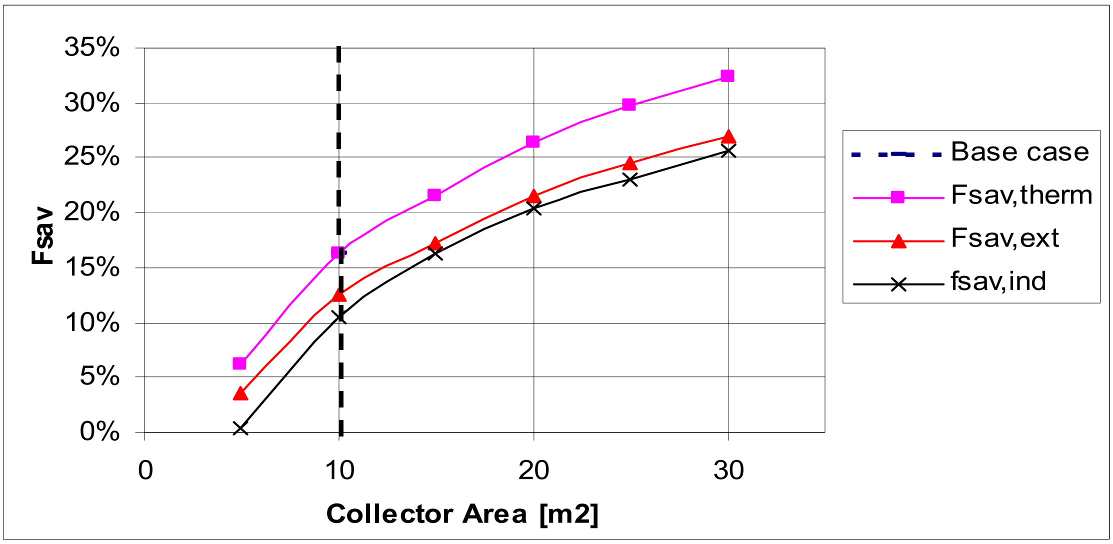


Fig. 3. Variation of fractional energy savings with collector size with fixed specific store volume of 0.074 m^3/m^2.

Differences from Base Case

The heights for the inlet/outlet of the upper/lower collector heat exchanger and 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 (0.16 m^3).
- A “dead” volume of 1% of the store volume exists above the upper DHW heat exchanger’s outlet.
- 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.
- The sensors for the thermostats controlling the store charging, upper collector and lower collector controller sensor were always the same in relation to the outlet positions (0.06 / 0.1/0).
- The height of the store was constant.

Description of Results

The savings increase with increasing collector area, the increase being larger than with fixed store volume.

Comments

None

Sensitivity parameter :	**Store Size [m3]** **(fixed collector area of 10 m^2)**	**0.37 – 2.5 m^3**

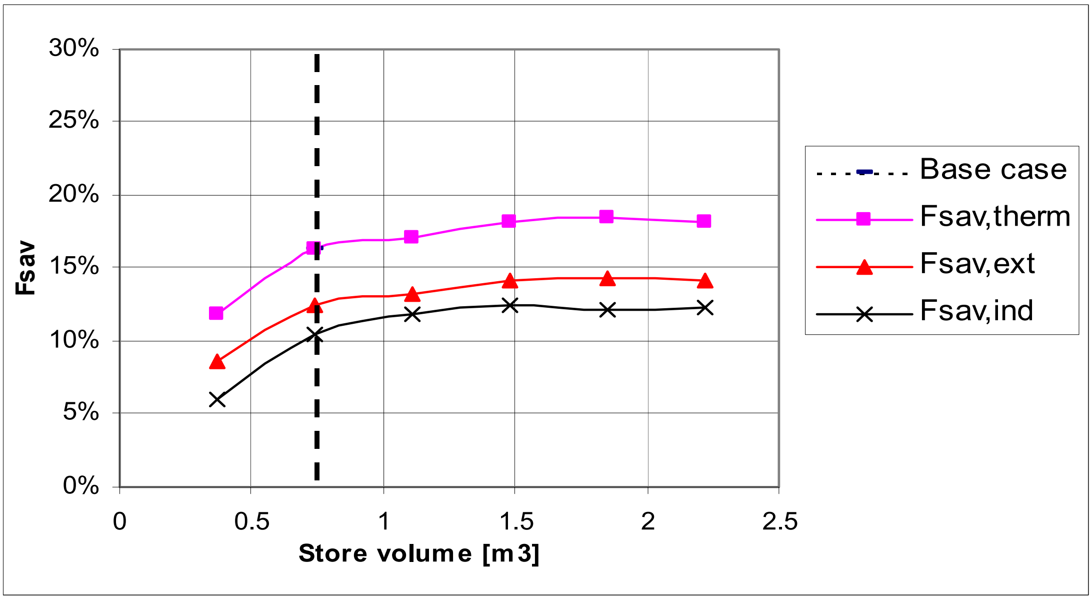


Fig. 4. Variation of fractional energy savings with store volume with fixed collector area of 10 m^2.

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 (0.16 m^3).
- A "dead" volume of 1% of the store volume exists above the upper DHW heat exchanger's outlet.
- 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.
- The sensors for the thermostats controlling the store charging, upper collector and lower collector controller sensor were always the same in relation to the outlet position. (0.06 / 0.1/0).
- The height of the store was constant

Description of Results

Here the savings show an optimum between 1.5 and 2.0 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 savings slightly decrease due to the increasing of heat losses from the store (year round).

Comments

Penalties are larger for volumes above 1.5 m3, but these are dependent on the assumptions on where the inlets/outlets should be placed when the volume changes.

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

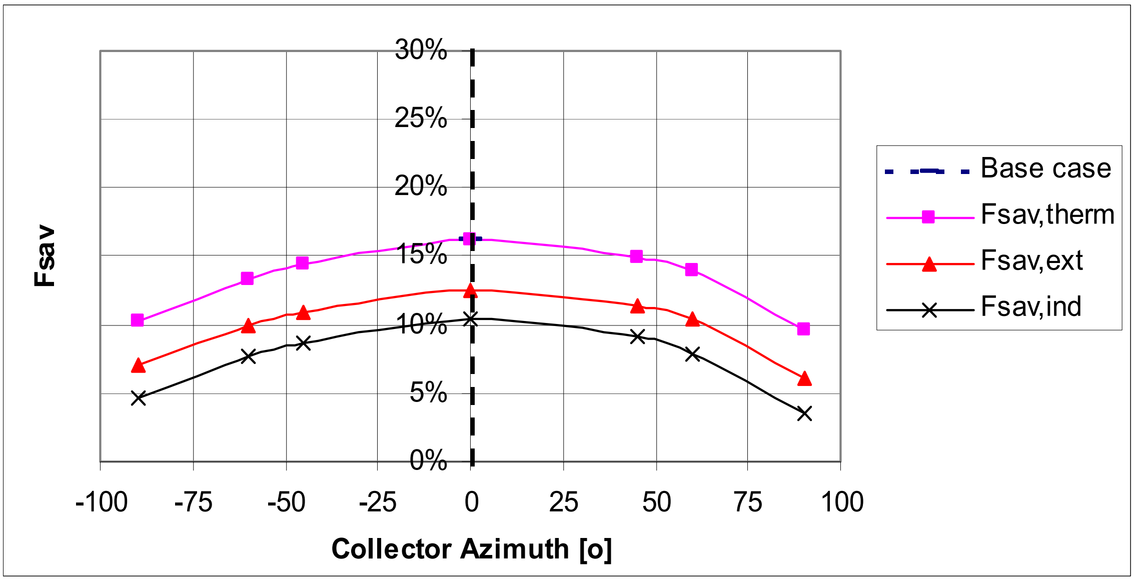


Fig. 5. Variation of fractional energy savings with collector azimuth with fixed tilt angle of 45°.

Differences from Base Case
None

Description of Results
Here the savings show an optimum at around 0°.

Comments
None.

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

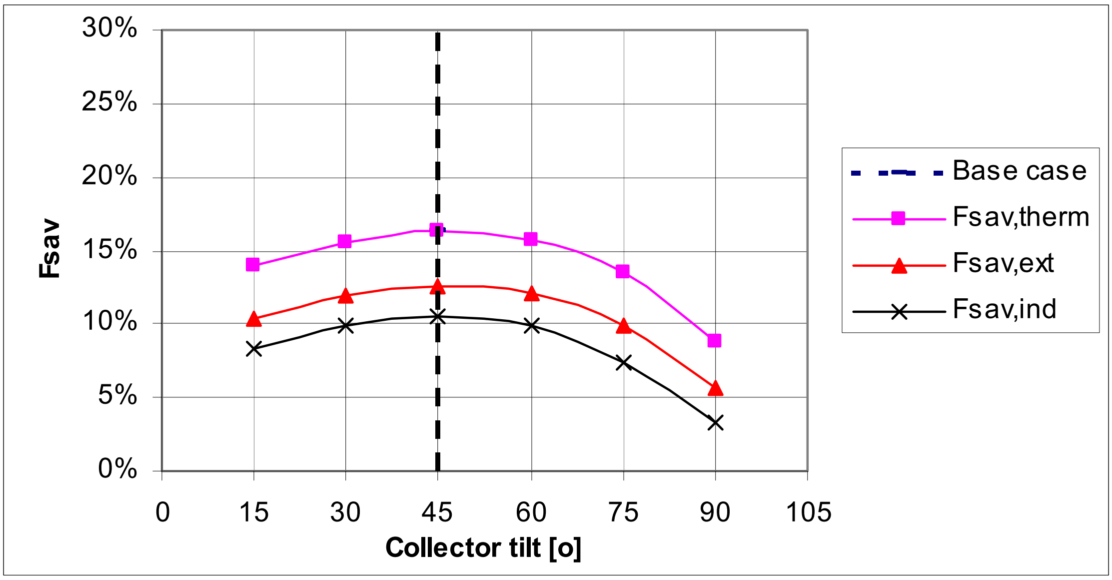


Fig. 6. Variation of fractional energy savings with collector tilt, with fixed azimuth angle of 0°.

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 optimum tilt angle is greater when a greater space heating load is required in relation to the DHW load.

Comments
None.

Sensitivity parameter :	**Upper Collector Heat Exchanger Outlet Rel. Height [-]**	**0.3 – 0.75**

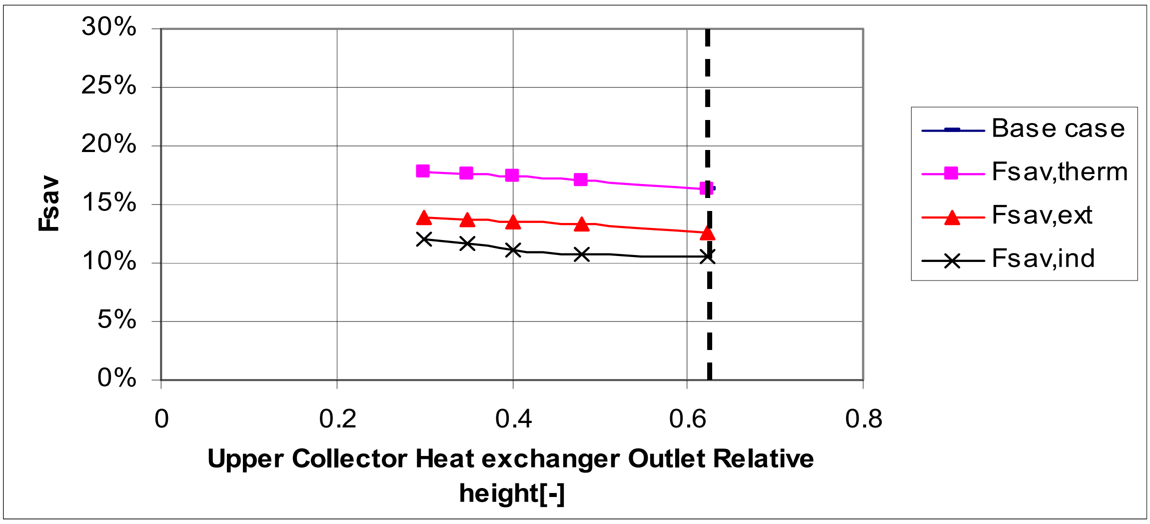


Fig. 7. Variation of fractional energy savings with the position of the upper collector heat exchanger's outlet, with fixed vertical extension of 0.13 for the heat exchanger. Heights are relative heights (=actual height / total height of store)

Differences from Base Case

None

Description of Results

Here the savings decrease with the increasing of outlet height. The positions of the lower DHW and lower collector heat exchangers and space heating outlets were unchanged during these simulations.

Comments

None.

Sensitivity parameter :	**Lower Collector Heat Exchanger Outlet Rel. Height [-]**	**0.05 – 0.295**

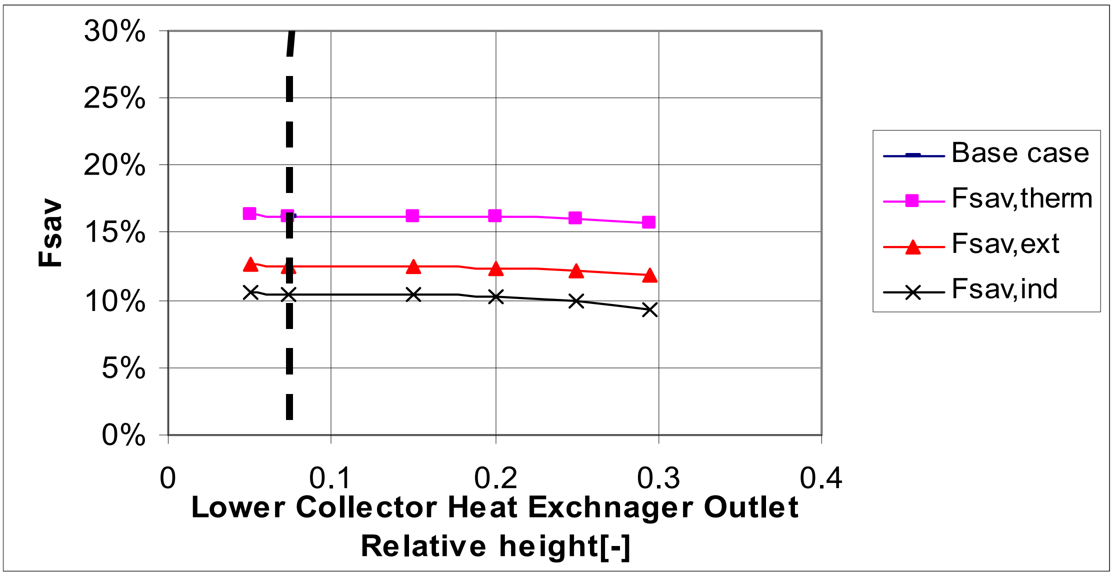


Fig. 8. Variation of fractional energy savings with the position of the lower collector heat exchanger's outlet, with fixed vertical extension of 0.16 for the heat exchanger. Heights are relative heights (=actual height / total height of store)

Differences from Base Case
None

Description of Results
Here the savings are nearly constant up until an outlet height of about 0.15, after which they drop slightly. The position of the lower DHW heat exchanger was unchanged during these simulations.

Comments
None.

Sensitivity parameter :	**Lower DHW Heat Exchanger Inlet Rel. Height [-]**	**0.05 – 0.295**

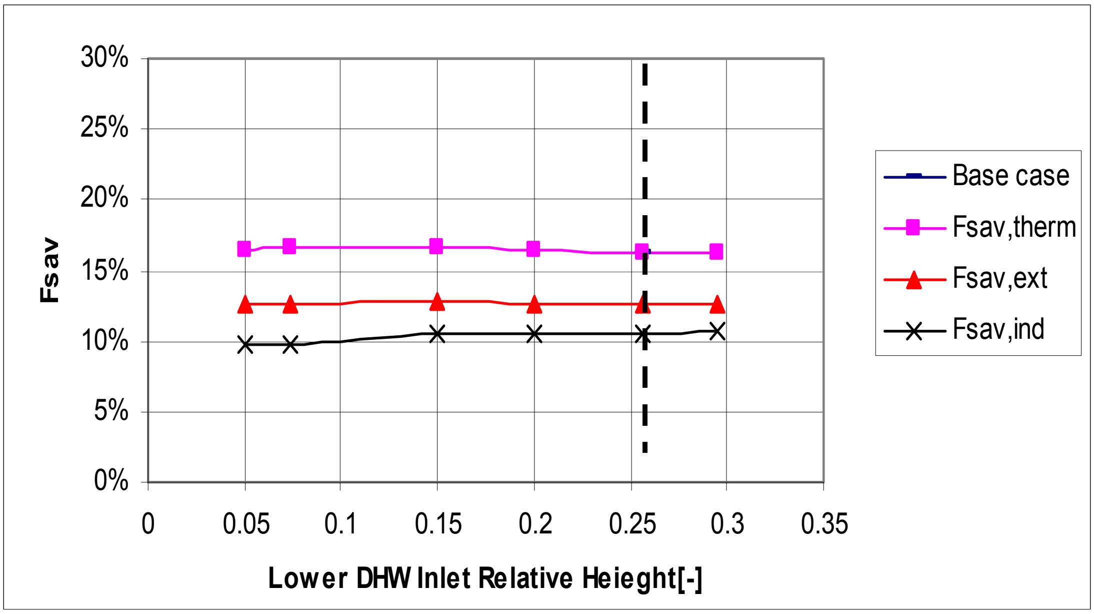


Fig. 9. Variation of fractional energy savings with the position of the lower DHW heat exchanger's inlet, with fixed vertical extension of 0.16 for the heat exchanger. Heights are relative heights (=actual height / total height of store)

Differences from Base Case
None

Description of Results
Again here the savings vary very little over the range simulated, although there is a flat optimum at about a height of 0.15. However, the Fsi value decreases significantly below 0.15 showing that the below this value the DHW load is not met as well.

Comments
None.

Sensitivity parameter :	Upper DHW Heat Exchanger Outlet Rel. Height [-]	0.78 – 1.000

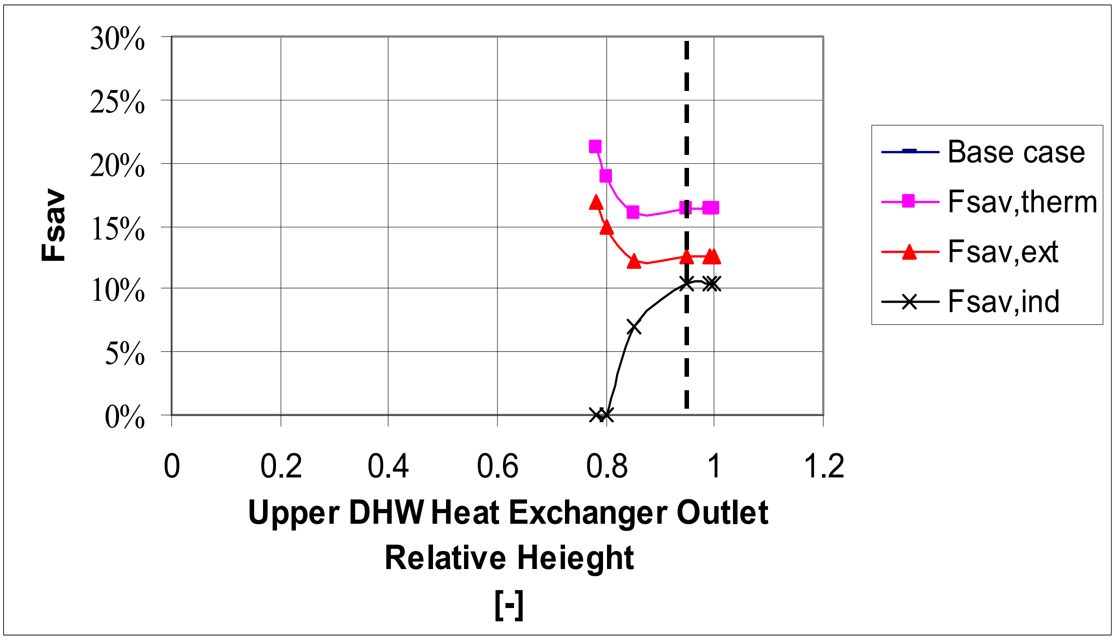


Fig. 10. Variation of fractional energy savings with the position of the upper DHW heat exchanger’s outlet, with fixed vertical extension of 0.06 for the heat exchanger. Heights are relative heights (=actual height / total height of store)

Differences from Base Case
None

Description of Results
Here the savings increase for lower heights, but only due to the fact that the DHW load is not fully met. Heights of 0.95 and 1.00 give very similar results.

Comments
The thermostat/controller settings for auxiliary charging of the store were unchanged for these simulations. If these settings are changed then results would probably changed. The results are likely to be load dependent.

Sensitivity parameter :	**Boiler Inlet Rel. Height [-]**	**0.51 – 1.0**

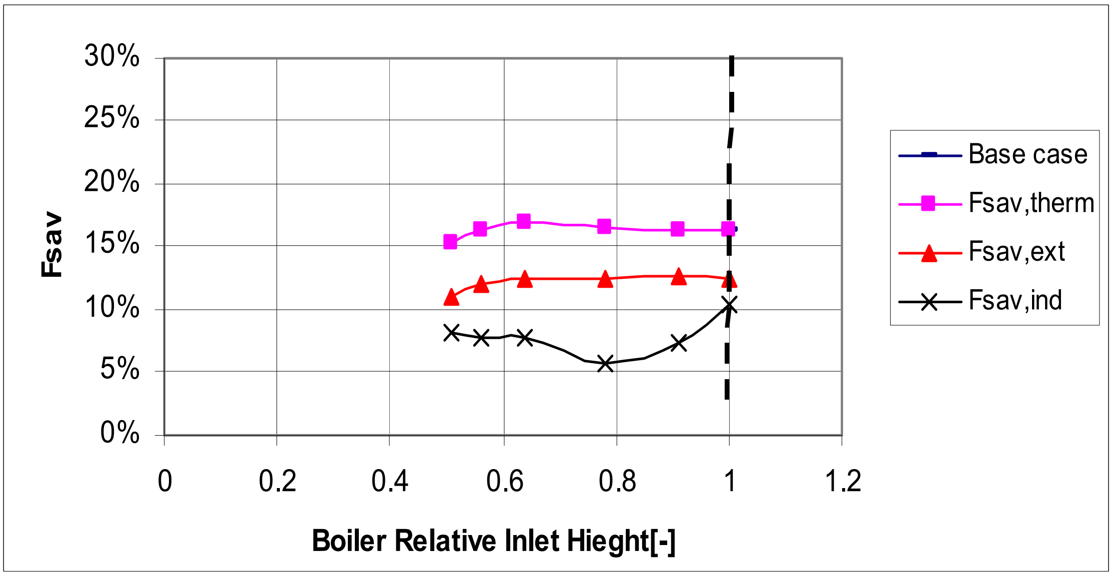


Fig. 11. Variation of fractional energy savings with the position of the boiler inlet. Heights are relative heights (=actual height / total height of store)

Differences from Base Case
None

Description of Results
There is an optimum of savings at approx. 0.65 for the inlet height. However, this is associated with a larger difference in Fsav,ext, indicating that the store is being charged over longer periods resulting in higher pump consumption. There are also significant DHW penalties for most of the range indicating that only the inlet of 1.00 is suitable here.

Comments
None.

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

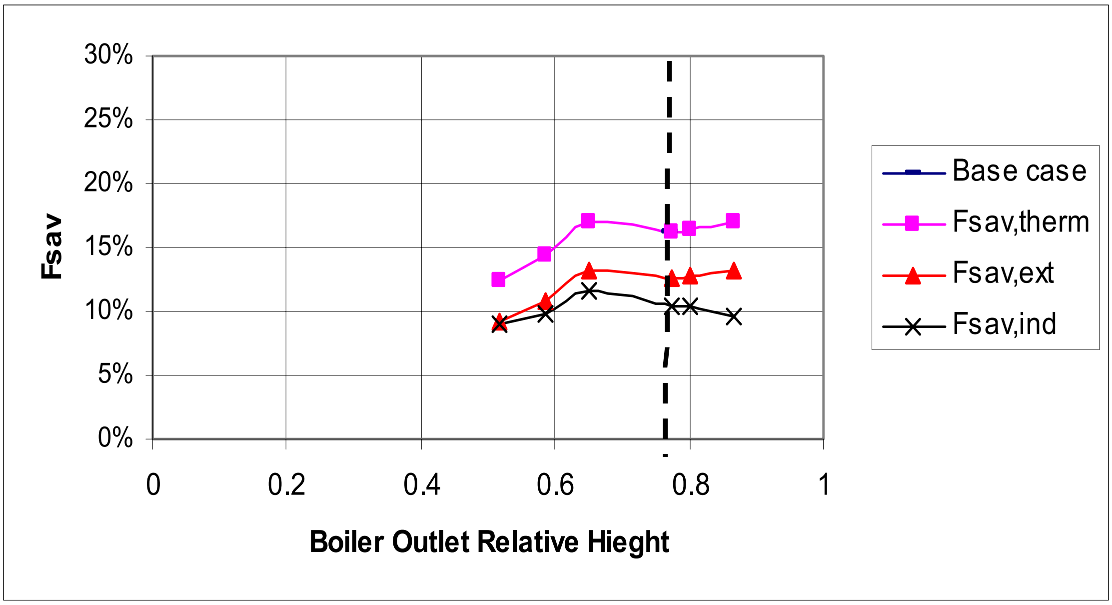


Fig. 12. Variation of fractional energy savings with the position of the boiler outlet. Heights are relative heights (=actual height / total height of store)

Differences from Base Case
None

Description of Results
The penalties increase with increasing outlet height. A maximum value for savings occurs at outlet heights of approx. 0.65 and 0.85, but only that at 0.65 is valid due to the penalties. This is a better value than the base case value of 0.77 both for savings and penalties.

Comments
The thermostat/controller settings for auxiliary charging of the store were unchanged for these simulations. If these settings are changed then results would probably changed. The results are likely to be load dependent. The electrical heater was always at same height of 0.77.

Sensitivity parameter :	**Auxiliary Heated Volume [m^3]**	**0.14 – 0.35**

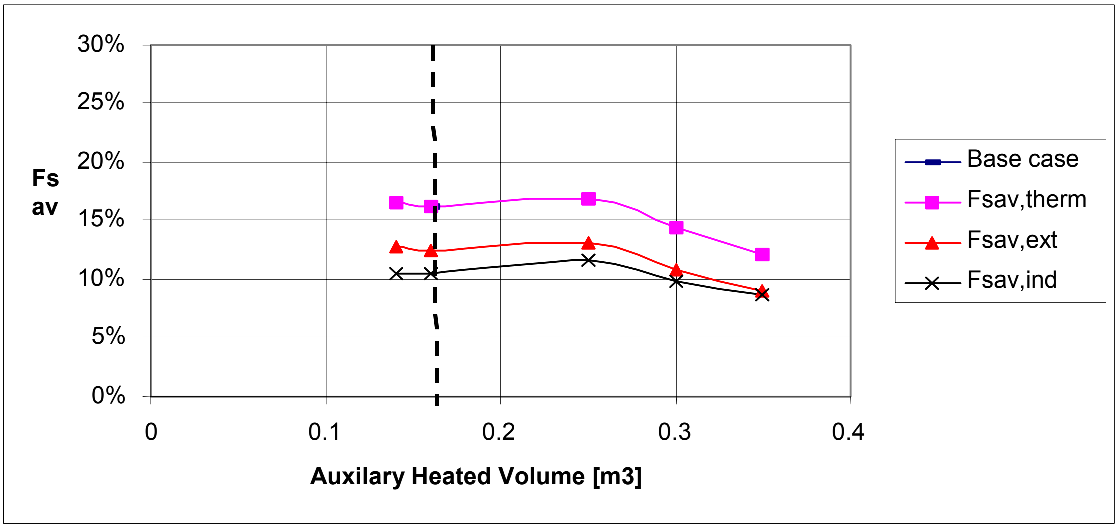


Fig. 13. Variation of fractional energy savings with auxiliary heated volume.

Differences from Base Case
None

Description of Results
These results are similat to those for the boiler outlet height showing an optimum volume of approx. 0.25 m^3. With these simulations both the boiler outlet and electrical heater were moved.

Comments
The thermostat/controller settings for auxiliary charging of the store were unchanged for these simulations. If these settings are changed then results would probably changed. The results are likely to be load dependent.

Sensitivity parameter :	**Heating System Inlet Rel. Height [-]**	**0.1 – 0.550**

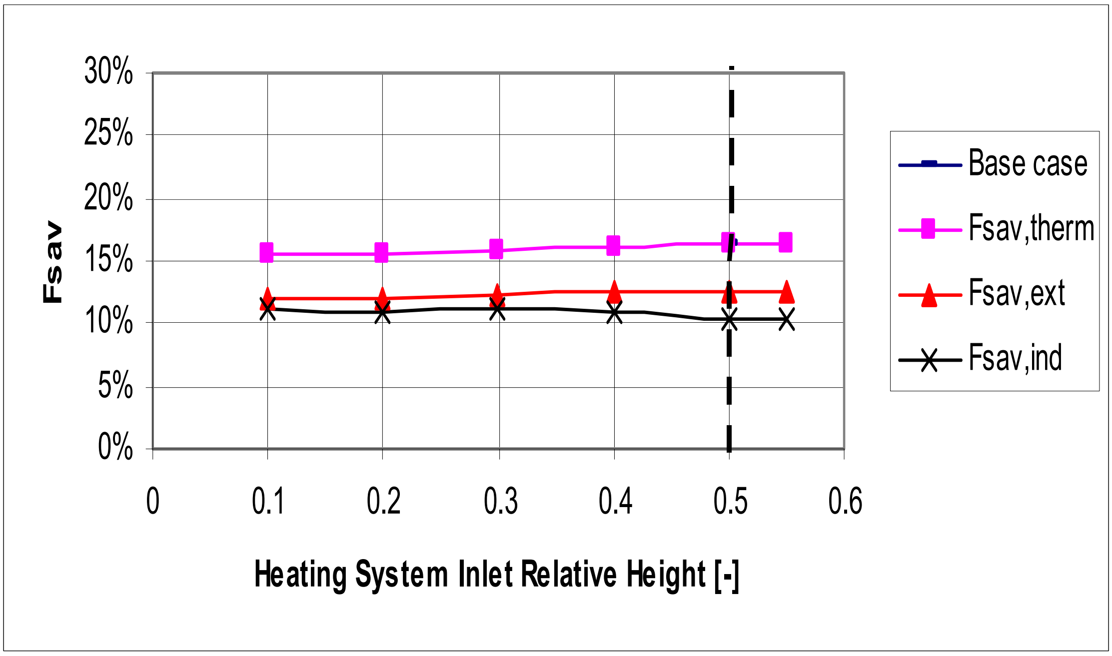


Fig. 14. Variation of fractional energy savings with the position of the heating system inlet (return). Heights are relative heights (=actual height / total height of store)

Differences from Base Case
None

Description of Results
The savings increase slightly with increased heating system inlet height. However, the penalties also increase.

Comments
None.

Sensitivity parameter :	**Lower Heating System Outlet Rel. Height [-]**	**0.483 – 0.827**

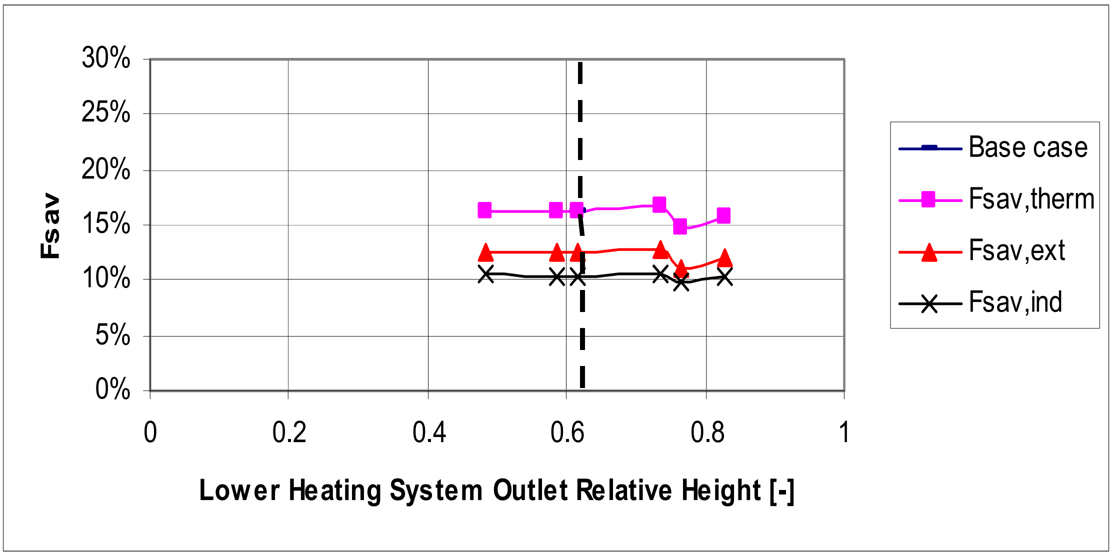


Fig. 15. Variation of fractional energy savings with the position of the lower heating system outlet (flow). Heights are relative heights (=actual height / total height of store)

Differences from Base Case
None

Description of Results
The optimum inlet height is at approx. 0.75, which is just below the auxiliary heated volume (boiler outlet at 0.77). The dip in the curves coincides with the position of the boiler outlet height (ie the start of the auxiliary heated volume).

Comments
None.

Sensitivity parameter :	**Upper Heating System Outlet Rel. Height [-]**	**0.72 – 1.0**

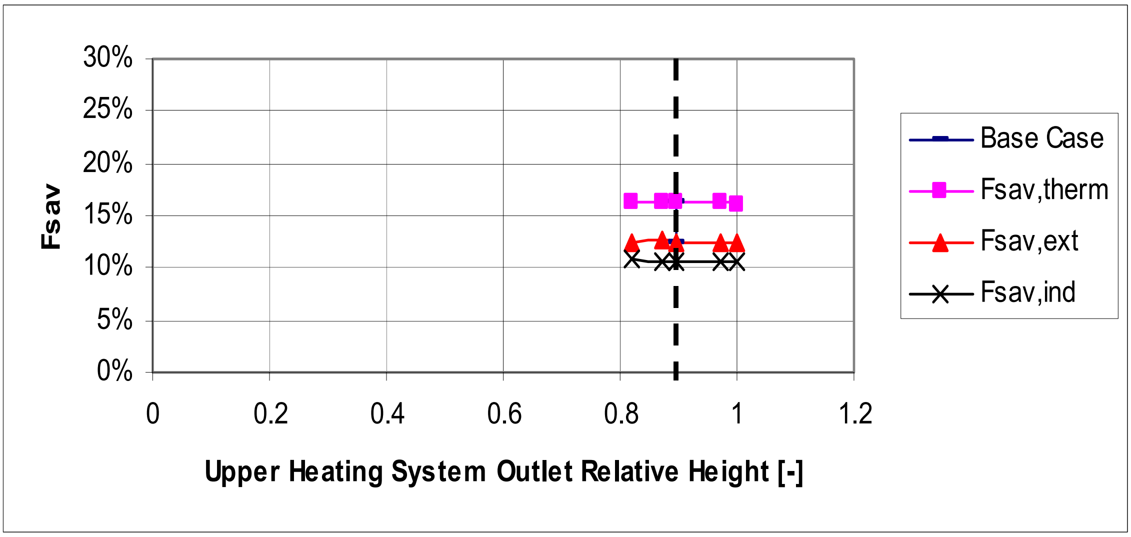


Fig. 16. Variation of fractional energy savings with the position of the upper heating sysgtem outlet (flow). Heights are relative heights (=actual height / total height of store)

Differences from Base Case
None

Description of Results
There are insignificant variations in savings with this parameter.

Comments
None.

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

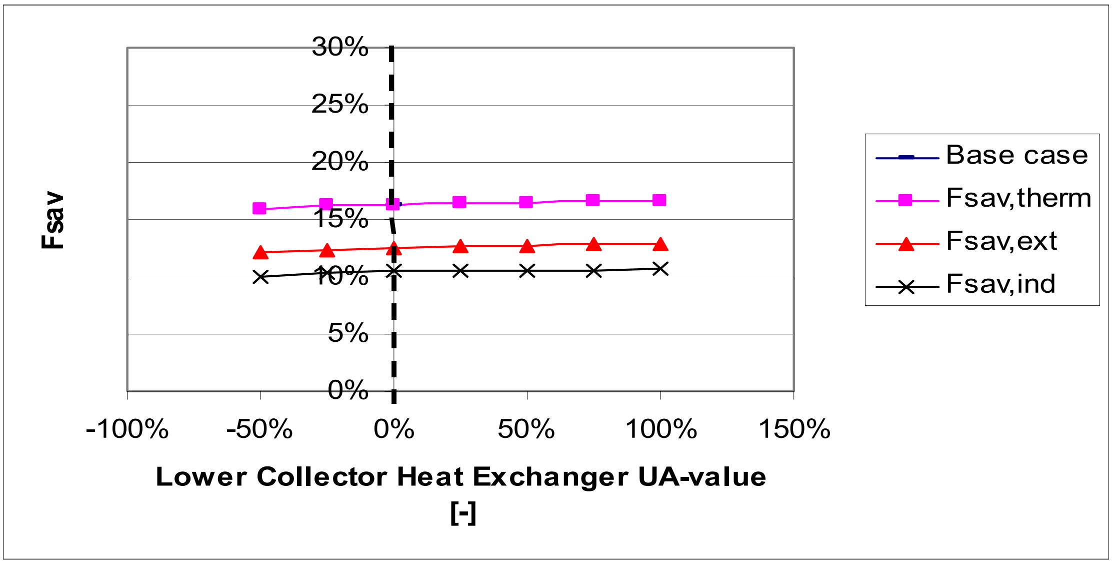


Fig. 17. Variation of fractional energy savings with the UA-value of the lower collector heat exchanger. Parameter values are relative to that identified from measurements.

Differences from Base Case
None

Description of Results
Here the savings increase with the increasing of UA- value. Below the base case value (identified from measurements), the savings decrease slightly. Above this value there is only a marginal improvement in the savings.

Comments
None.

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

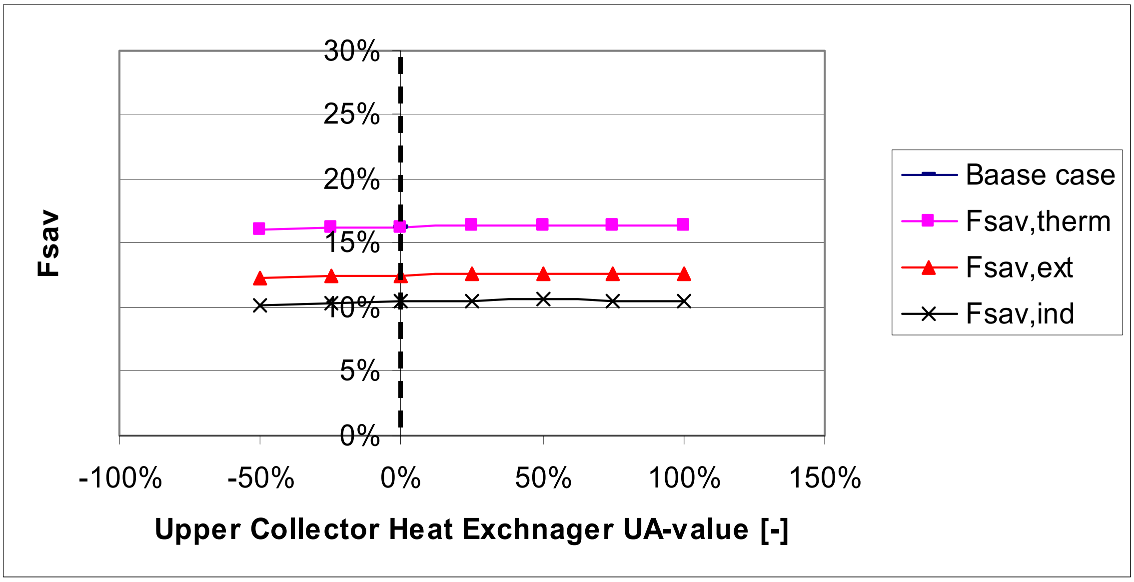


Fig. 18. Variation of fractional energy savings with the UA-value of the upper collector heat exchanger. Parameter values are relative to that identified from measurements.

Differences from Base Case
None

Description of Results
Here the savings vary insignificantly over the range simulated. Below the base case value (identified from measurements), the savings decrease slightly. 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%**

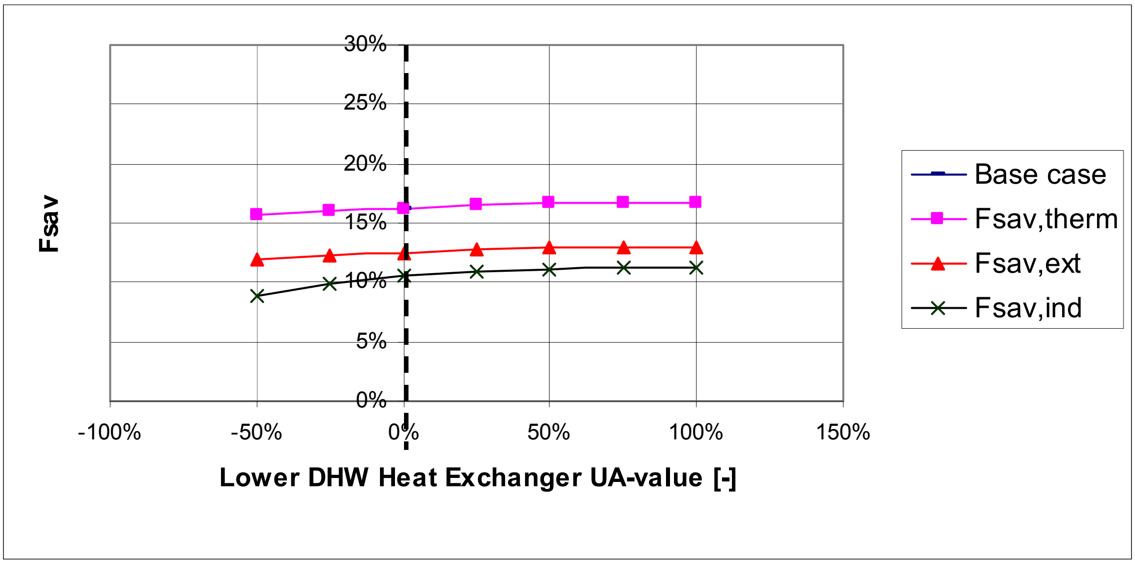


Fig. 19. Variation of fractional energy savings with the UA-value of the lower DHW heat exchanger. Parameter values are relative to that identified from measurements.

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 slight improvement in the savings. There is also a significant increase in penalties below the base case value.

Comments

The thermostat/controller settings for auxiliary charging of the store were unchanged for these simulations. If these settings are changed then results would probably change. The results are likely to be load dependent.

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

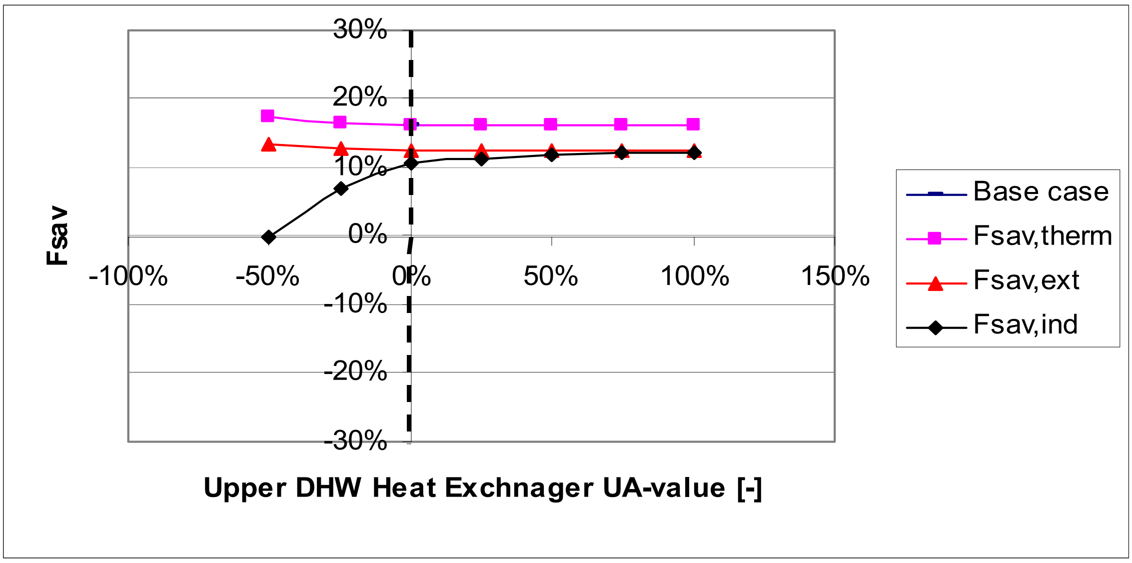


Fig. 20. Variation of fractional energy savings with the UA-value of the upper DHW heat exchanger. Parameter values are relative to that identified from measurements.

Differences from Base Case
None

Description of Results
Savings increase below the base case value but are constant above it. However, the penalties increase with decreasing UA-value, especially so below the base case value.

Comments
The thermostat/controller settings for auxiliary charging of the store were unchanged for these simulations. If these settings are changed then results would probably changed. The results are likely to be load dependent.

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

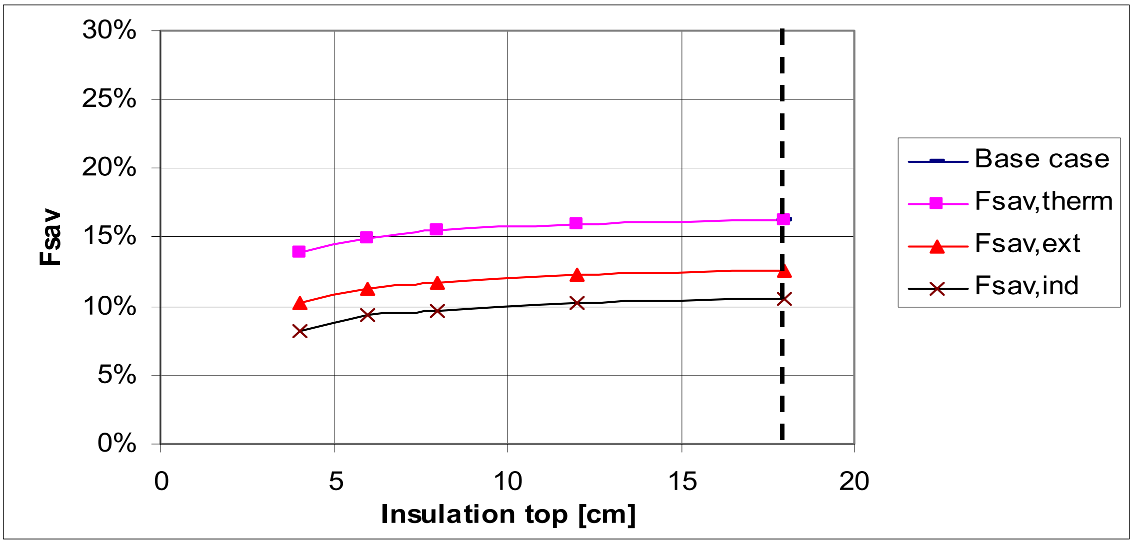


Fig. 21. Variation of fractional energy savings with the thickness of insulation on the top of the store.

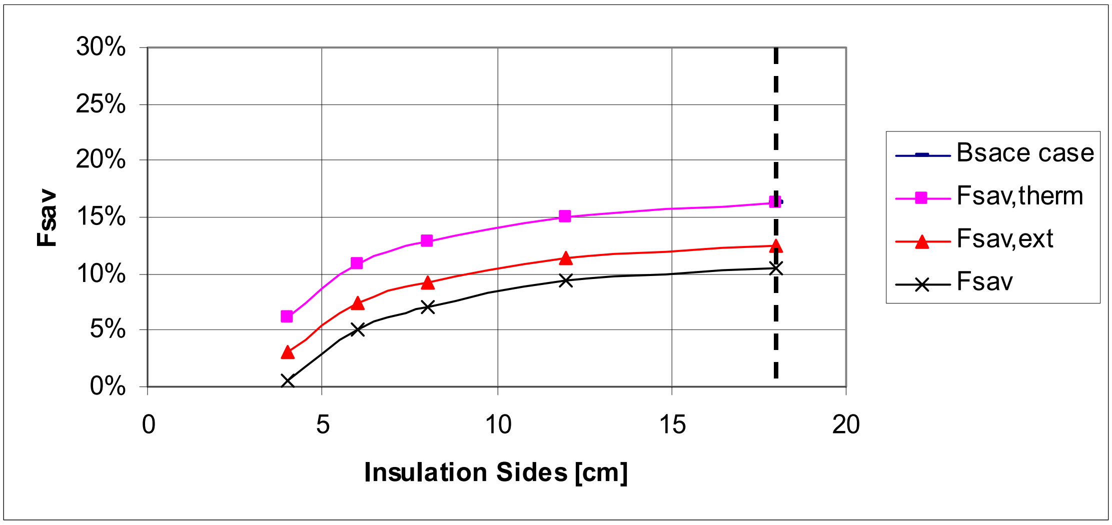
Differences from Base Case
None

Description of Results
Here the savings increase with increasing insulation thickness, which are expected results.

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 0.74 m^3.

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

Fig. 22. 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 savings again increase significantly with the increasing of insulation thickness.

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 0.74 m^3.

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

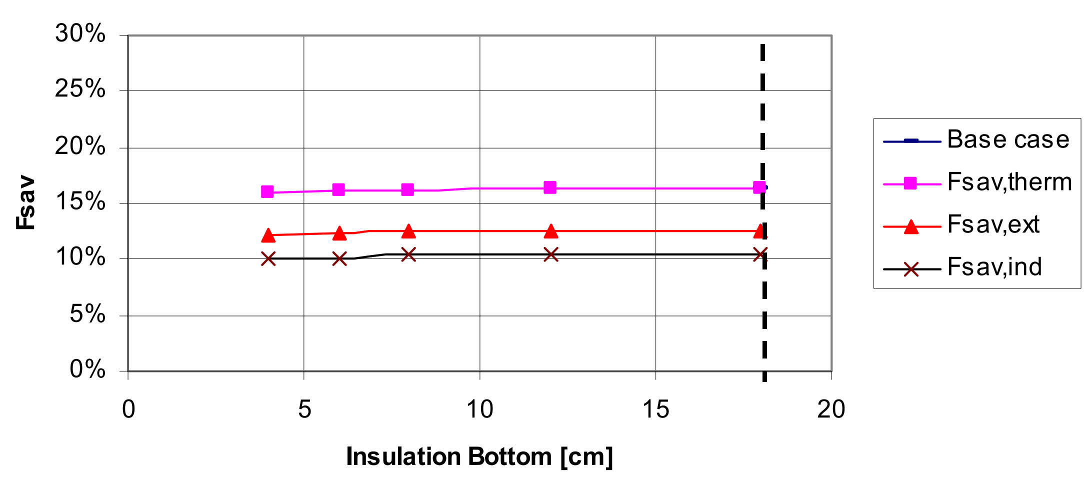


Fig. 23. Variation of fractional energy savings with the thickness of insulation on the bottom of the store.

Differences from Base Case

None

Description of Results

Here the savings vary insignificantly over the 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 0.74 m^3.

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

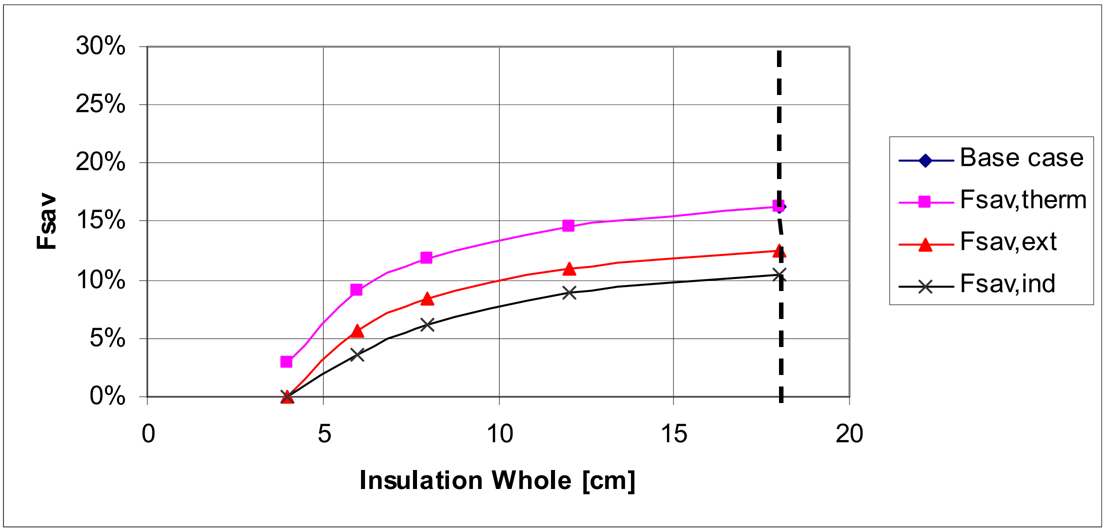


Fig. 24. Variation of fractional energy savings with the thickness of insulation around the whole store.

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 0.74 m^3.

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

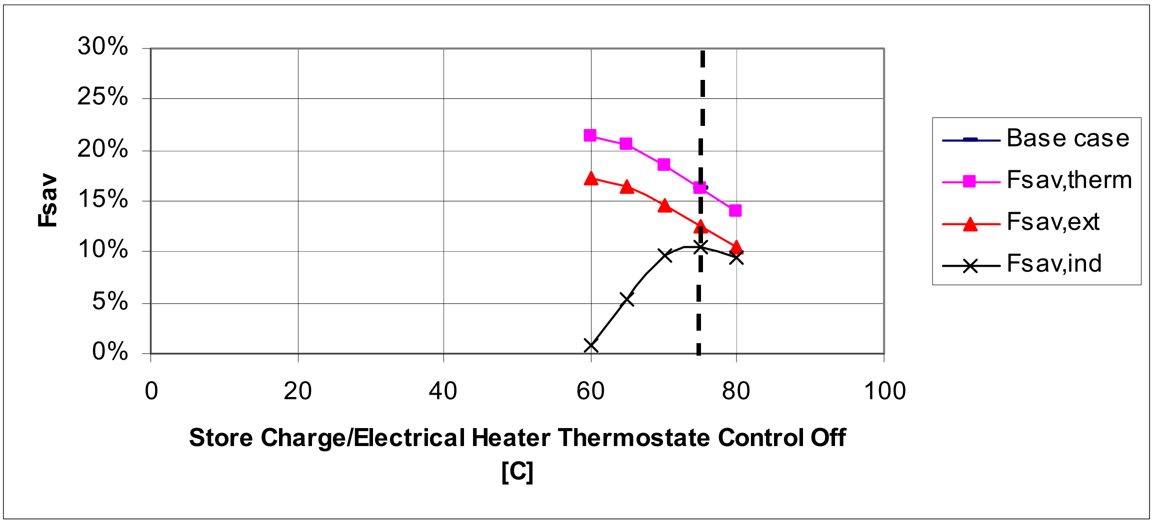


Fig. 25. Variation of fractional energy savings with the store charge controller settings. Values shown are for the charge turn off (upper bound) of the controller.

Differences from Base Case

None

Description of Results

The savings decrease very significantly with increasing thermostat setting. Below the base case value, the penalties increase greatly.

Comments

The boiler standby and supply set temperature were set to be 5^{o}C higher than the thermostat (off) setting, and the hysteresis for the controller to 8K. The electrical heater is used in summer and set to be 5^{o}C lower than thermostat (off) setting.

Sensitivity parameter :	**Store Charge Controller Sensor Rel. Height [-]**	**0.0 – 0.12**

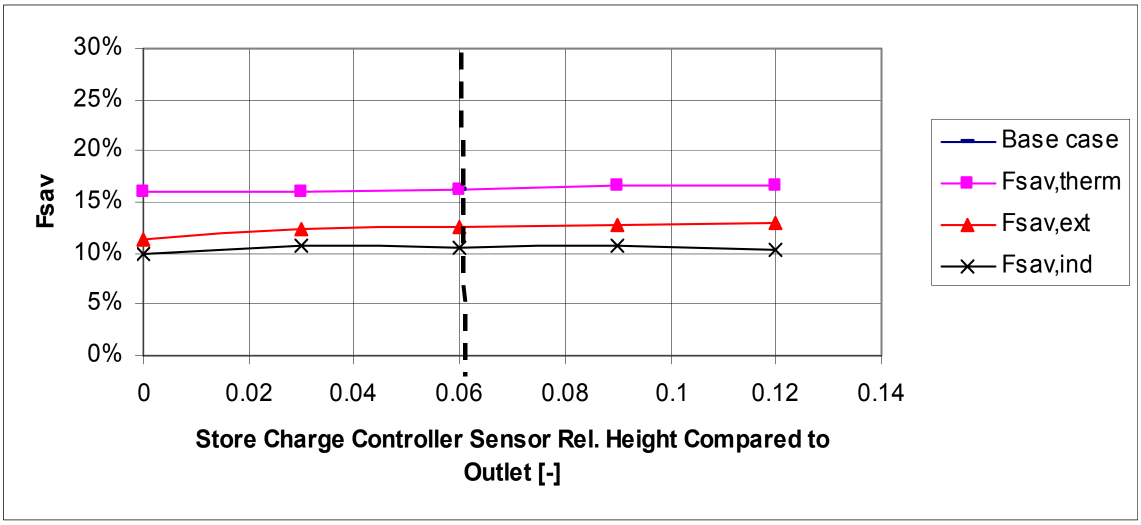


Fig. 26. Variation of fractional energy savings with the store charge controller's sensor position.

Differences from Base Case
None

Description of Results
Savings increase slighlty with increasing height of the thermostat sensor. However, at both ends the value of Fsi decreases, showing that the optimum position is approx. as for the base case value.

Comments
None.

Sensitivity parameter :	**Lower Collector Controller Sensor Rel. Height [-]**	**0.0 – 0.250**

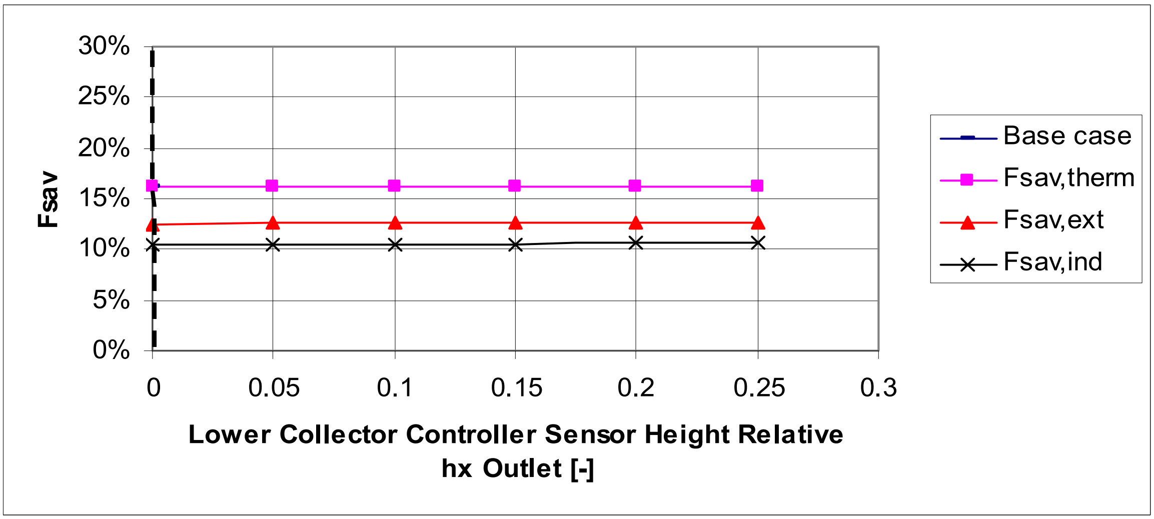


Fig. 27. Variation of fractional energy savings with the collector controller's sensor position.

Differences from Base Case
None

Description of Results
Here the savings remain constant over the range simulated.

Comments
None.

Sensitivity parameter :	**Upper Collector Controller Sensor Rel. Height [-]**	**0.0 – 0.250**

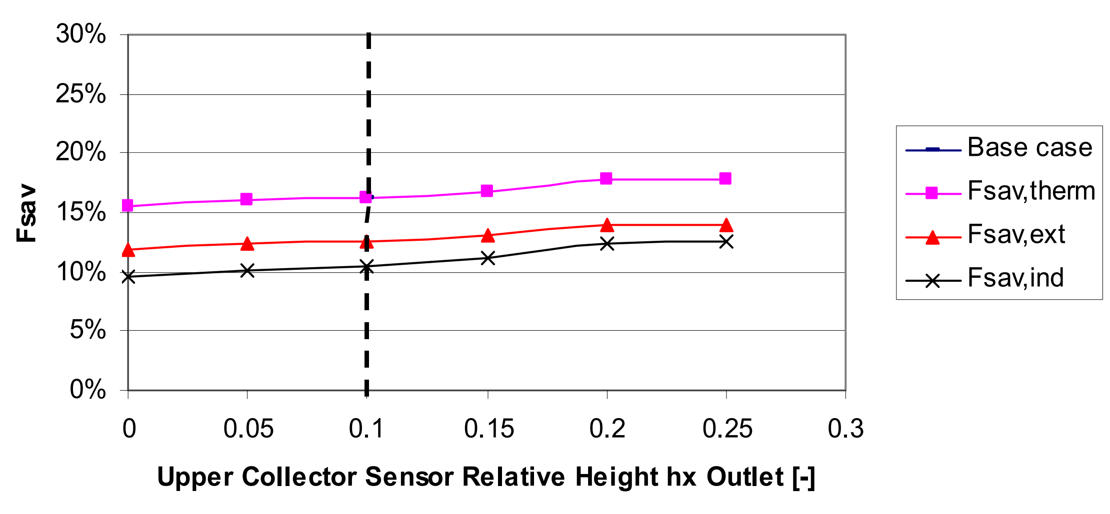


Fig. 28. Variation of fractional energy savings with the upper collector controller's sensor position.

Differences from Base Case
None

Description of Results
Here the savings vary significantly. Below the base case sensor relative height savings slightly decrease and above this height savings increase. Results show that the optimum upper collector sensor relative height heat exchanger is at 0.25 higher than the heat exchanger outlet.

Comments
The upper collector heat exchanger is hardly used. A higher sensor position decreases the use of the upper heat exchanger. This indicates that better results are achieved if the upper heat exchanger is not used at all.

Sensitivity parameter :	**Controller dTupstart [^{o}C]**	**5-10 ^{o}C**

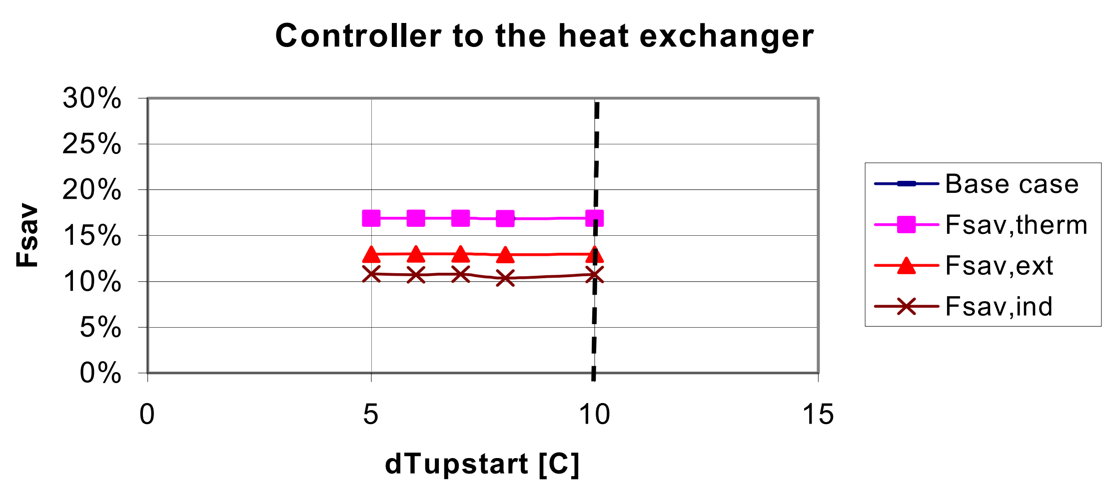


Fig. 29. Variation of fractional energy savings with the upper collector controller's temperature.

Differences from Base Case
None

Description of Results
There are only small variations over the range simulated.

Comments
dT upstart parameter describes the temperature difference between the outlet temperature (T1) of fluid from collector and store temperature (T4) by the lower heat exchanger required to switch the flow from lower to upper collector heat exchanger.

Sensitivity parameter :	Controller dTstart [^{o}C]	1-4 ^{o}C

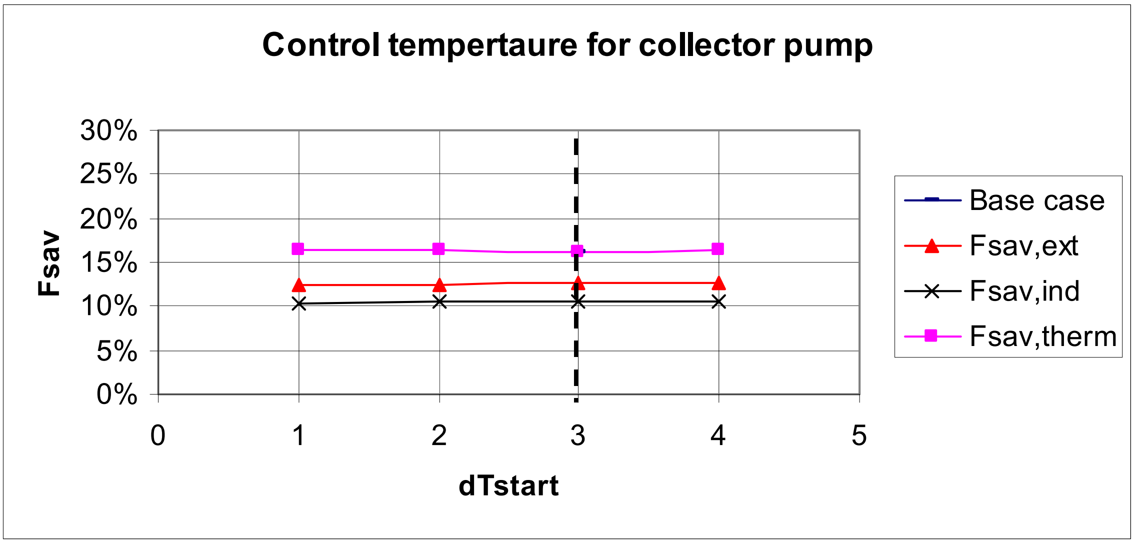


Fig. 30. Variation of fractional energy savings with the control temperature of collector pump.

Differences from Base Case

None

Description of Results

There is very little variation over the range simulated.

Comments

dT start is the required temperature difference between the outlet temperature of fluid from collector (T1) and the store temperature by lower heat exchanger (T4) to start the pump.

Sensitivity parameter :	**Tube Insulation Thickness [cm]**	**5 – 30 cm**

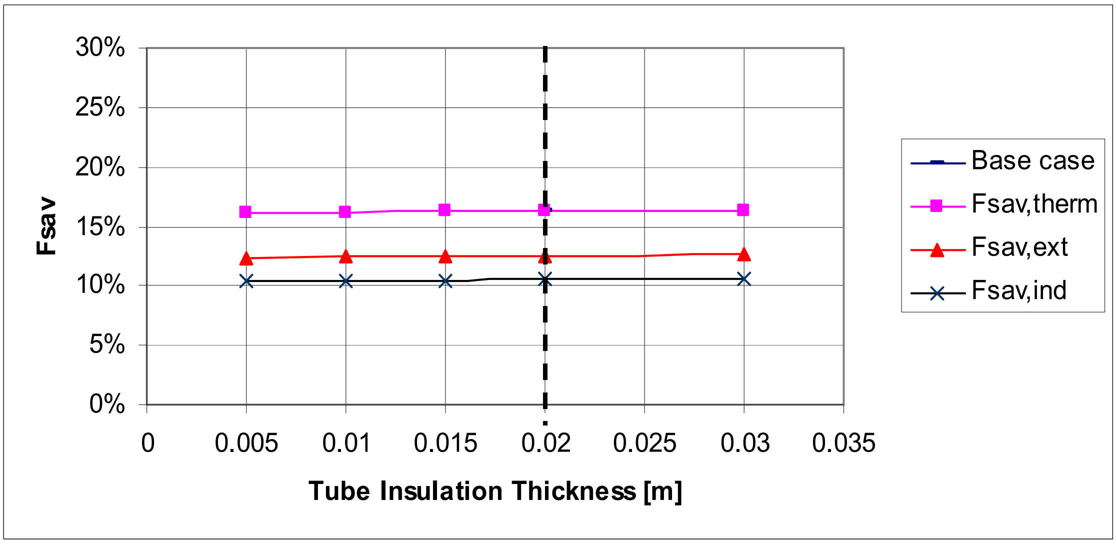


Fig. 31. Variation of fractional energy savings with the insulation thickness round the collector tubing.

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 was15 mm external diameter. No correction factor for “imperfections” was included.

4.2 Optimisation of the System

Initial optimisation work based purely on the sensitivity analysis did not produce great improvements, apart from reducing the penalties to an acceptable level while maintaining the savings to similar levels. For these conditions it was shown that by not using the upper heat exchanger at all, the same or better savings could be achieved.

This was an unexpected result and further investigations were carried out. These revealed that the extra collector heat exchanger has a much greater and beneficial effect if the store is larger than is usual, that is if the store has a high specific volume. For twice the specific volume in Stockholm it was shown that the two heat exchangers provide greater savings than just one.

A second stage of optimisation was then applied using an automatic optimisation tool, in this case GenOpt. Several different optimisations were performed to find out which of the two following alternatives was more effective: **high-flow** (with some variation) in the collector loop using either the upper or the lower heat exchanger as originally designed; **low-flow** in the collector loop using either both or only the lower heat exchanger.

In these optimisations the value that was minimised was: Qburnsol + Qpen45, that is the boiler energy usage plus the hot water penalty. The Stockholm climate and the SFH60 building were used. Based on the cost optimisation of System #11 it was decided to use a larger heat exchanger in the upper part of the store for preparation of hot water. The same value was used as in the cost optimised System #11. The following table shows the best results of these optimisations.

Concept	Qburnsol [kWh]	Qpen45 [kWh]
high-flow	15479	14
low-flow	15627	96

Both these optimised concepts were significantly better than the values achieved previously. However, the high-flow (original design) proved to be best. The values for these were thus used for the definition of the optimised system.

4.3 Definition of Optimised System

Based on the automatic optimisation of the system, the following optimised system has been defined for the conditions of Task 26. In this optimisation it was assumed that the lower outlet to the space-heating loop should be placed just below the outlet to the boiler. In addition the size of the upper DHW heat exchanger and the placement of the lower DHW heat exchanger were fixed to the same values as found during the optimisation of System #11. The system is the same as defined for the base case for System #12 apart from the following:

Auxiliary volume: 0.20 m^3, equivalent to relative height of 0.72 for the electrical heater and the outlet to the boiler.
Thermostat setting for store charge: 48/56°C.
Boiler set temperature: 70°C.
Lower collector heat exchanger. Inlet 0.03, outlet 0.19.
Upper collector heat exchanger. Inlet 0.52, outlet 0.39.
Lower DHW heat exchanger: Inlet 0.05, outlet 0.60.
Upper DHW heat exchanger: Twice the UA-value compared to the base case. Assuming a linear relationship between surface area and UA-value, this means 22 m of 22 mm diameter finned coil tube. Inlet at 0.83, outlet at 0.99.
Space-heating connections: Upper outlet 0.90, lower outlet 0.68, inlet 0.44.
Controller settings. Two settings for the collector controller were optimised.

4.4 Comparison to System #11

There are three main differences between systems #11 and #12:

- An extra heat exchanger in the collector loop.
- A four-way instead of a three-way valve for supplying heat to the space-heating system. This takes water from the below the auxiliary heated zone in preference to above, and therefore uses more solar heated water.
- An advanced controller that switches between the collector heat exchangers and varies the flow when the radiation is on the border of being enough to supply heat to the store.

The advance control function could not be studied in detail properly as the weather data was in the form of hourly data, so sharp variations did not occur in the simulations. This function is designed to make the most of varying radiation. In order to study the affect of the other two differences, System #12 was simulated for a load and climate combination that shows maximum difference between the performance of System #11 and #12. This was Carpentras SFH100 and 10m^2. This was simulated for two volumes with all combinations of having/not having the second heat exchanger and the 4-way valve. The results are shown in the table below. In the case of one heat exchanger only the lower is used.

Store Volume [m^3]	**Solar Heat Exchangers**	**Space-Heating Supply**	**$F_{sav,th}$**
0.74	2	4-way valve	44.42%
0.74	1	4-way valve	44.35%
0.74	2	3-way valve	43.87%
0.74	1	3-way valve	43.79%
1.50	2	4-way valve	46.93%
1.50	1	4-way valve	45.39%
1.50	2	3-way valve	45.12%
1.50	1	3-way valve	44.65%

The results show that for the standard size of store for the collector area, 0.74 m^3, the extra collector heat exchanger gives very little improvement whereas the 4-way valve gives a significant improvement. However, for a larger volume of 1.5 m^3, both the extra heat exchanger and the 4-way valve give significant improvements in performance, and the combination of the two gives an even greater improvement.

5 Analysis using FSC

Fig. 32 shows the FSC characteristic for systems #11 and #12. There are four cases for System #11, and 2 for #12, both depicted using dashed lines. It can be readily seen that the base case for System #12 is slightly better that that of System #11 but worse than the optimised versions of System #11. However, the optimised System #12 is the best of all variations shown here. The gas boiler is modelled as with the standard Task 26 parameter values and connections.

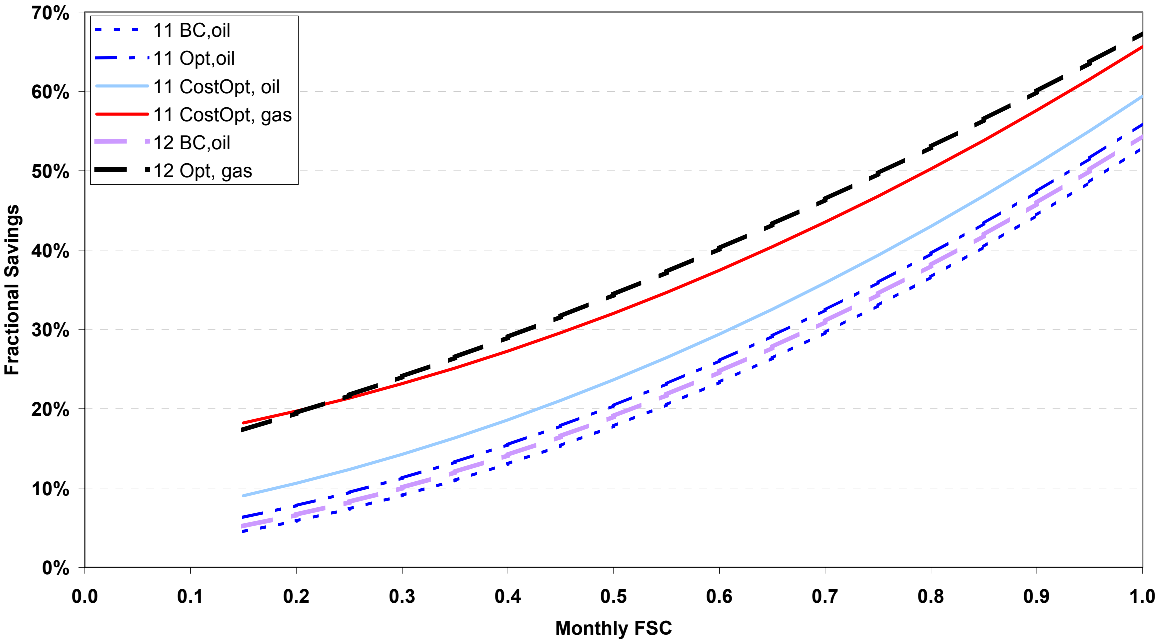


Fig. 32. FSC characteristic for System #12 in the base case simulation model (BC) and optimised version with gas boiler. Characteristics for four version of System #11 are also shown as a comparison.

When the size of the system is altered, then the placement of heat exchangers is not necessary suitable and excessive penalties may occur. This was the case with System #12. Here slight alterations in the thermostat settings were required to avoid excessive penalties for DHW preparation. In addition the placement of the upper collector and lower DHW heat exchangers were adjusted so that they did not extend into the auxiliary heated volume. For the optimised system the following conditions applied:

Collector Size [m2]	Store Volume [m3]	Lower DHW Heat Exch. In/out	Upper coll. Heat Exch. In/out	Thermostat Set Temp. [°C]
5	0.50	0.05/0.54	0.45/0.32	60
10	0.74	0.05/0.60	0.52/0.39	56
20	1.50	0.05/0.60	0.75/0.62	56

In addition to the above, the electrical heater was turned on and boiler off for the hours defined in section 6.1. This is in principal for the period without space heating.

6 Description of Components Specific to This System

6.1 Switch Between Winter and Summer Seasons for System #12

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

6.2 Microsolar Controller for Collector Circuit

This is a model (type 145) of the specific controller for this system. It controls the switching of the flow between the upper and the lower heat exchanger and even the flow-rate used, all depending on the store temperatures, and the temperature in the collector and in the pipes. A special temperature sensor is used in the collector. It is mounted on a absorber strip separated from the absorber connected in the circuit. This gives a better indication of the stagnation temperature, although it is in reality in between the stagnation temperature and the current collector outlet temperature. For the simulations it was assumed to be exactly midway between these two temperatures.