

DOMESTIC HOT WATER SYSTEMS: TESTING, DEVELOPMENT, TRENDS

U. Frei, P. Vogelsanger and D. Homberger

Institut für Solartechnik SPF

Hochschule Rapperswil HSR

Oberseestrasse 10, CH-8640 Rapperswil

Phone: +41 55 222 48 21, Fax: +41 55 210 61 31, E-mail: ulrich.frei@solarenergy.ch

www.solarenergy.ch

Abstract - The basis for system development is accurate and reproducible system testing. Since more than 10 years, the solar energy laboratory SPF is involved in system testing. Many systems have been tested according to different approaches.

Well proved to investigate new concepts is the component based method, where dynamic fitting in conjunction with TRNSYS is applied to each of the different components. Variation of components in the systems (e.g. heat exchanger, solar collector) demonstrate further possibilities for improvements. According to this component based method, more than 30 systems have been tested in the last 5 years at SPF.

Comparison of different concepts are discussed in order to see advantages and disadvantages of low-flow to normal flow concepts. Also the pros and cons of helix heat exchangers to mantle tanks are discussed by comparing the most efficient storage tanks coupled to identical collectors.

1. INTRODUCTION

Solar technologies, such as solar thermal, possess a huge future potential. This is not denied, even by the people from the lobby of the conventional energies, e.g. the oil or gas industries. But not in all countries the market is growing like it used to in the last years (Austria, Switzerland, Denmark)! Reasons are different but it seems that the small marked segment of the idealistic ecologists connected with ideal constraints (funding etc.) are now equipped with solar systems. To augment the market, new market segments have to be found. In the area of domestic hot water systems this means, the so called „early buyers“ must be persuaded to invest in such a system. The only way to do this, is to improve the systems performance while lowering their costs to bring their energy prices near conventional systems. Simultaneous the technical status as well as the appearance must be highly professional. The current developments go towards advanced smart systems of which all components are designed and optimized to fit to the overall system. This approach leads to the so called „kit“-systems where in the scope of delivery all necessary components are included (collectors, storage tank, pump and so forth).

In Switzerland this approach has been introduced into the market with success since 1996. Figure 1 shows the market evolution.

The idea of kit systems is penetrating also into the area of combisystems (combination of solar domestic hot water and solar heating system) and the solar domestic hot water preheating systems for large multifamily houses.

An important advantage of the kit-system is, that they can be tested and optimized in the laboratory. If this task is

done consequently, system specific components have to be developed. Especially for the main components such as the storage tank and the solar collectors this is a difficult and expensive exercise! Therefore in a number of kit systems available on the market, standard components are used. The remaining question is, whether these systems including standard components have an acceptable performance compared to the kit systems including especially designed components.

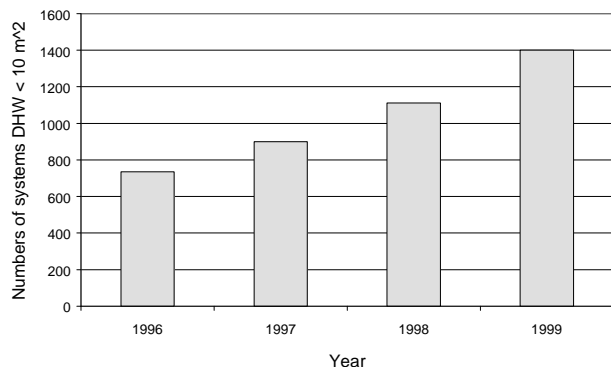


Figure 1: Marked trend of small domestic hot water systems

Important design features in these systems are the operating conditions in the solar loop (Low-flow versus High-flow), the heat exchanger principal (heat exchanger spirals contra mantle heat exchangers), the tubing (integral, all in one envelope contra traditional tubing) or the solar collectors (flat plate contra evacuated tubular collectors).

2. SYSTEM TESTING

At SPF, Rapperswil the CTSS (Component Test and System Simulation) method is used for solar domestic hot water system testing /1/. The systems are installed completely and with their solar collectors outdoors. A variety of sensors are fitted to assess the performance of the different components, such as: storage tank, collectors, pump, collector loop piping. A typical simplified measurement set-up is illustrated in figure 2. With a series of short dynamic test sequences and subsequent parameter identification a performance model of each component can be derived. Using TRNSYS /2/ the performance of the system can be calculated. Simulations with measured boundary conditions may be used for validation purposes. Arbitrary boundary conditions are used for standardized annual performance predictions.

The boundary conditions for simulation

- The collectors plane is at a tilt angle of 45 degrees and faces south.
- The solar radiation in the collector plane and the ambient temperature was generated using Meteororm /3/ for the location Rapperswil, Switzerland.
- Domestic hot water load: The average daily domestic hot water (DHW) load volume is 200 litres at 45°C. In terms of energy, the annual DHW consumption amounts to about 3000 kWh/a. The draw-off pattern is identical to the one used at SPF for standard annual performance predictions with eight draw-offs per day. The draw-off pattern is identical on every day of the year. There is a seasonal dependency of the mains water temperature: The average is 9.5 K, the amplitude 5 K. The lowest mains temperature is reached on February 10.
- The auxiliary heating is enabled only between midnight and 6 a.m. Restricting the operation of the electrical auxiliary heater to nightly hours reflects the usual set-up for DHW-preparation in Switzerland.
- The storage ambient temperature is 18°C.

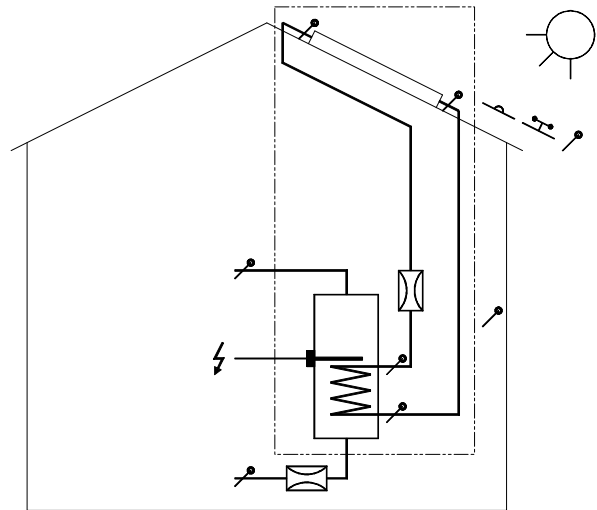


Figure 2: Simplified measurement set-up

System configuration

- The solar systems (size; mode of operation; settings, e.g. overheating protection) are configured exactly as they were submitted for testing by the manufacturers. The only type of auxiliary heating used is the integrated electrical heating element. The auxiliary heater set points and the on/off temperature differences were determined during the system test. With these auxiliary heater settings, the system is just able to meet the DHW demand without the hot water temperature dropping below 45°C if the mains temperature is 10°C and if there is no energy input from the solar collectors.

3. SYSTEM DESCRIPTION

Test systems A₁ to A₆

The test systems A₁ to A₆ represent the most simple ones. Their storage tanks are usually mass produced, made of enamelled steel and contain just one heat exchanger spiral in the lower part to transfer the solar energy to the domestic water. In the upper part a second heat exchanger is included to use an oil, gas or wood fired furnace as auxiliary source. In addition about half of the volume (150 to 250 l) can be heated by electricity. As already mentioned above this is because of the special Swiss circumstance to use cheap off peak night time electricity as auxiliary energy.

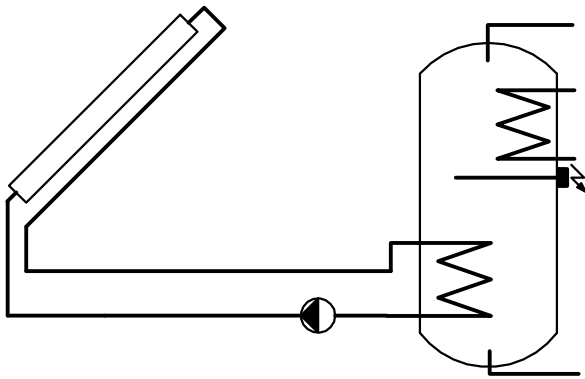


Figure 3: Scheme test systems A₁ to A₆

Test systems B₁ to B₃

The most significant difference to the test systems A is the additional solar heat exchanger in the upper part of the storage tank. But there are more differences: the operating mode of the collector loop is changed from standard to low-flow. This means the storage design, including the heat exchangers should support significant stratification. Depending on the feeding temperature the solar energy is directed to the upper heat exchanger before passing through the second one in the lower part. Under regular operating conditions the return temperature should be kept low, in a good low-flow design, just a few degrees over the cold water temperature. Depending on solar insolation the temperature difference over the collector can reach 50°C leading directly to convenient

hot water temperature in the range of 60 to 70°C in the uppermost part of the storage tank.

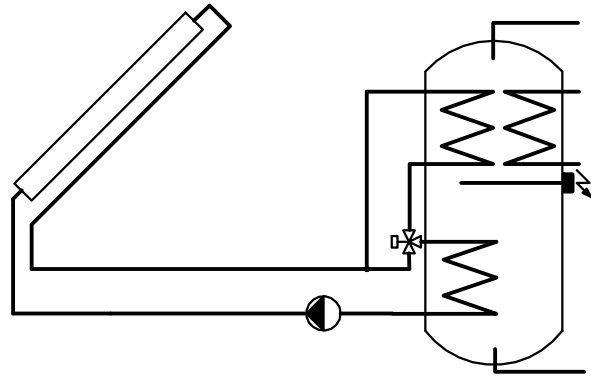


Figure 4: Scheme test systems B₁ to B₃

Test systems C₁ and C₂

As can be seen in figure 5 the test systems C₁ and C₂ show a quite different design! Instead of spiral heat exchangers double mantles are used. The advantage of double mantle heat exchangers are their large area, their low turbulence effects on the storage water and last but not least their excellent stratification behaviour. To maintain these advantages an adapted design is required. Both systems use different entrance heights depending on feeding and tank temperature.

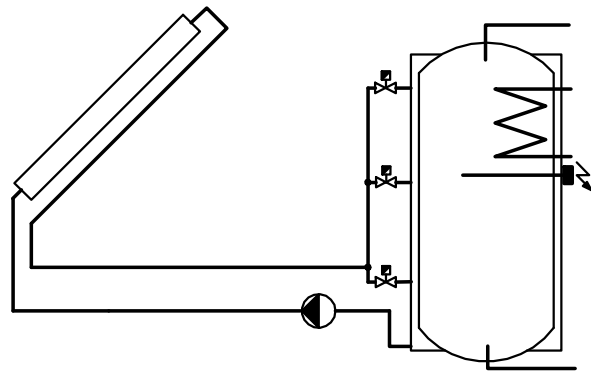


Figure 5: Scheme test systems C₁ and C₂

Table 1: Description of the systems

System features / system number	A ₁	A ₂	A ₃	A ₄	A ₅	A ₆	B ₁	B ₂	B ₃	B ₄	C ₁	C ₂
Tank design: 1: system specific, custom made 2: standard tank large scale production	2	2	2	2	2	2	1	2	2	1	1	1
Storage tank content, litre	407	370	480	387	484	469	450	529	463	381	428	459
Heat exchanger principle: 1: helix 2: mantle tank	1	1	1	1	1	1	1	1	1	1	2	2
Area solar heat exchanger bottom part, m ²	1.8	1.4	2	1.4	1.9	2	2	1.5	1	1.5	-	-
Area solar heat exchanger top part, m ²	-	-	-	-	-	-	1.2	1.2	1	0.7	-	-
Area mantle heat exchanger, m ²	-	-	-	-	-	-	-	-	-	-	2.3	3.9
Volume heated only by the solar collectors, litre	245	197	277	219	230	253	179	266	232	203	268	192
Volume heated by the electrical auxiliary heater, litre	162	173	203	168	254	216	271	263	231	178	160	267
Storage tank material: 1: stainless steel, 2: enamelled steel	2	2	2	2	2	2	1	2	1	2	2	1
Storage tank weight, kg	135	90	252	205	190	133	75	310	110	159	135	100
Storage tank insulation thickness, mm	125	75	75	50	Min. 54	80	75	120		85	100	80
Absorber area, m ²	5.3	5.5	5.3	6.9	4.5	5.9	4	5.3	4.8	5.4	4.1	6.1
Optical efficiency solar collector	0.798	0.784	0.795	0.789	0.819	0.809	0.834	0.795	0.773	0.816	0.859	0.834
Collector efficiency at $x = 0.1 \text{ m}^2\text{K/W}$, (x: red. temp. diff.)	0.314	0.269	0.4	0.364	0.343	0.4	0.41	0.4	0.3	0.4	0.37	0.42
Specific flowrate, l/m ² (absorber area)	56	38	11	40	12	51	15	21	22	14	13	13
Absorber type: 1: meander, 2: manifolds with parallel strips, 3: cushion absorber	2	2	1	2	1	2	1	1	2	1	3	1
Tubing type: 1: „integral tubing“, 2: traditional tubing	2	2	1	2	1	1	1	1	1	1	1	1
Pipe inner diameter, return pipe / feeding pipe, mm	13/13	12/12	10/10	16/16	8.6/8.6	13.4/13.4	10/10	10/10	13.4/13.4	8/8	10/10	6/8
Pump: 1: centrifugal pump, 2: positive displacement pump	1	1	1	1	1	1	2	1	1	2	1	2

4. SIMULATIONS AND DISCUSSION OF RESULTS

In this chapter results of different simulations are presented and discussed. The starting point are the results of the as tested systems. Since all systems are marketed in Switzerland they are optimized according to specific Swiss design criteria as presented in the next section. For the following steps of simulation the systems were changed to compare different aspects of system design.

Country specific design criteria

The criteria to design solar domestic hot water systems depend on a number of boundary conditions:

- Climate (location, solar insolation, cold water temperature ...)
- typical comfort needs (demand per typical family, temperature, typical daily or weekly variations)
- available auxiliary sources and their prices
- typical building conditions including location of the heating system (cellar, under the roof ...)
- building regulations

These criteria have a strong influence on the design of the system. As an example the conditions in Switzerland are described:

The Swiss climate varies significantly between the different meteorological regions. Typical mid European climate can be found where more than 80 % of the population is living but also the alpine or the southern part is not neglectable.

In Switzerland, especially in single family houses, electricity is still one of the main energies used for domestic hot water heating. Very important, using electricity as auxiliary energy, is the different price for day and night time electricity respectively. In general, night time off peak electricity is at least a factor of two cheaper than during day time. This circumstance has a strong influence on the dimensioning of the solar domestic hot water storage tank!

An other important design parameter is the required comfort level. From one country to another a variation of a factor two is possible. In Switzerland people use about 35 to 50 l of water heated from 10°C up to 45°C. A typical Swiss family of four persons need about 6 to 9 kWh of domestic hot water per day.

Set-up for the first set of simulations

- The auxiliary heater is enabled during night from midnight to 6 a.m.
- The auxiliary heater setting is able to meet the DHW demand without the hot water temperature dropping below 45°C if the mains temperature is 10°C and if there is no energy from the solar collectors.
- A constant daily load volume (200 l/day) with seasonally fluctuating mains temperature is used

(yearly consumption: 3000 kWh, average 8.2 kWh/day)

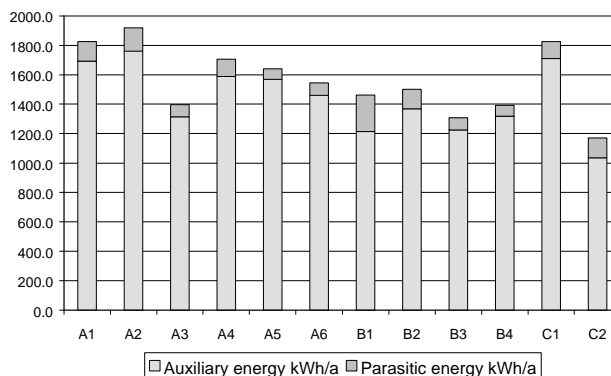


Figure 6: First set of simulation results of the as tested systems

The as tested systems show large differences in the necessary auxiliary energy to cover the load. Large differences in necessary auxiliary energy are shown for a number of systems.

The traditional systems with only one heat exchanger in the bottom of the tank, system A₁ and A₃ show a remarkable difference. Both have about equal collector and heat exchanger area. Responsible for the lower performance of system A₁ are the small auxiliary volume leading to a higher set temperature for the auxiliary source and the far poorer collector performance (at $x = 0.1 \text{ m}^2\text{K/W}$). Also outstanding is the large height of the heat exchanger and the low flowrate in the collector loop for system A₃, both features seem to have a positive effect on the system performance.

The B-systems perform all quite similar except for the high power consumption of system B₁ leading to an extraordinary high parasitic energy consumption.

The low-flow systems using mantle heat exchanger, C₁ and C₂, perform extremely different. Both systems designed for Swiss conditions shows a drastic difference in the auxiliary volume. System C₁ has just 160 l, which is leading to a very high set temperature and therefore reduces the efficiency of the whole system. In addition the collector area of systems C₁ is about 30% smaller than for system C₂.

Another way to present system performances is shown in figure 7:

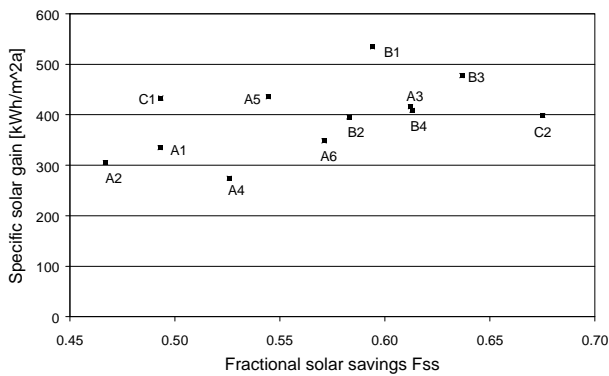


Figure 7: Solar fractional savings in relation to the specific solar gain (energy consumption reference system 3600 kWh/a) for the as tested systems

The figure shows clearly the enormous differences between the systems. Again the systems C₁ and C₂ perform very different, the reason is already discussed above. B₁, B₃, C₂, A₃ and B₄ are performing well.

Set-up for the second set of simulations

Compared to the first set of simulations, these elements of the boundary conditions were altered:

- The auxiliary heater is enabled during the day (between 6 a.m. and 10:30 p.m.), not during the night.
- For all the systems, the switch on temperature of the electrical auxiliary heater is 50 C, the switch off temperature is 52 C.
- The load file with daily and seasonal variations from Jordan /4/ was used to distribute the domestic hot water draw-off over the year. In this way the volumes and probabilities of different categories of DHW consumption are taken into account. With the combination of variable mains temperature and daily load volume the DHW load is significantly smaller in summer than in winter (see table 2 and figure 8).

The other parameters, including those of the auxiliary heater (power, on/off temperature difference and the orientation (vertical/horizontal) are not modified but left as they were during the testing of the system. The position of the auxiliary heater and with it the volume heated by the auxiliary heater is not modified with respect to the tested system either and was not modified in any of the simulations described. The auxiliary volume is thus different from one system to the other.

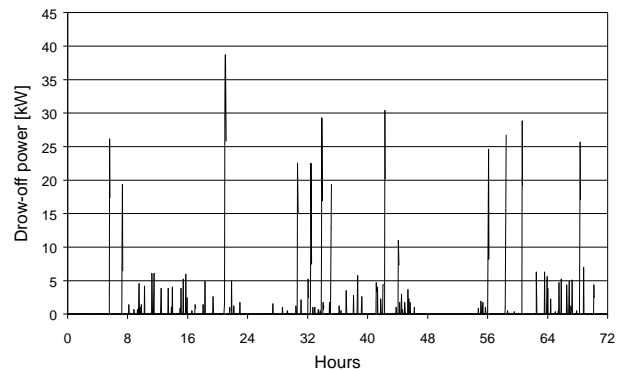
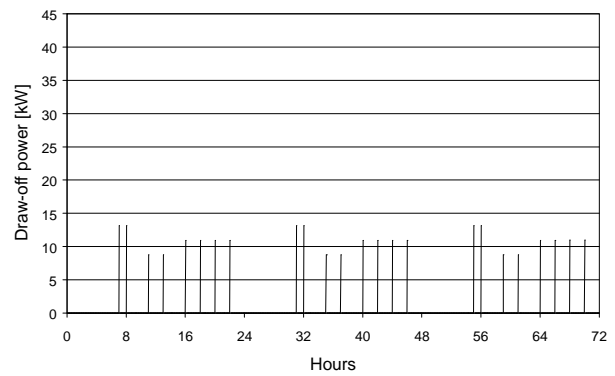
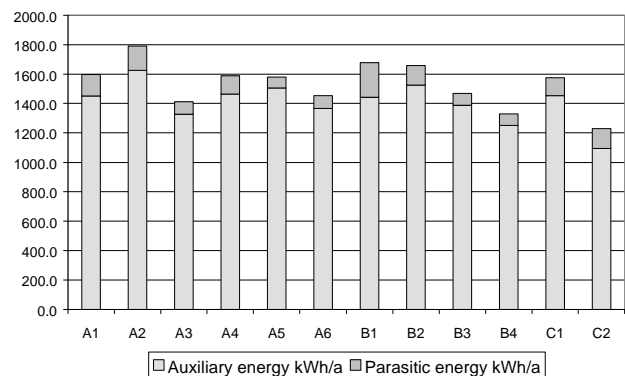


Figure 8: Comparison of the SPF to the Jordan draw-off profile

Table 2: Dependency of draw-off energy (kWh per month) for

- (1): a constant daily load volume and a seasonally fluctuating mains temperature
- (2): Jordan load file and a seasonally fluctuating mains temperature

	Jan	Feb	Mar	April	May	June
(1)	274.0	249.0	272.0	257.0	256.0	239.0
(2)	283.0	265.0	307.0	295.0	257.0	217.0
	July	Aug	Sept	Oct	Nov	Dec
(1)	241.0	240.0	235.0	250.0	251.0	268.0
(2)	196.0	183.0	240.0	237.0	263.0	287.0



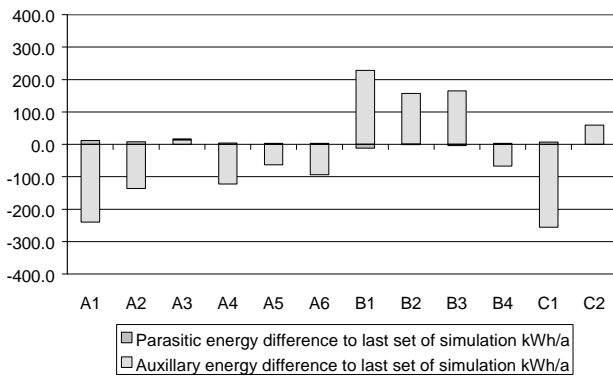


Figure 9: Second set of simulation results under the boundary conditions described above

The large influence on efficiency between the first and second set of simulations is initiated mainly by the change from night to day time auxiliary heating. The large auxiliary volumes of some of the systems is now – in contrary to first set of simulations – a disadvantage.

The lower auxiliary heating for system A_5 is caused by the lower hysteresis of the auxiliary source. In the as tested system, the hysteresis was in the order of 8 K which is now reduced to 2 K.

Conspicuous is the strong increase off auxiliary energy for the systems B_1 to B_3 . The main reason is, the large auxiliary volume but connected with the arrangement of the upper heat exchanger. It is assumed, that the temperature sensor controlling the auxiliary source is below the upper heat exchanger and therefore is turned on even if enough energy is available in the top part of the storage tank. This disturbs the positive effect of the second heat exchanger drastically.

Set-up for the third set of simulations

Compared to the second set of simulations the configuration of the systems was made uniform for all the systems in the following points:

- The position of the electrical heating element is horizontal and the vertical distance of the thermostat used to control the auxiliary heater and the heating element is identical for all systems. The power of the auxiliary heater is 3 kW.
- The only overheating protection used is: cease collector loop operation if the temperature in the storage tank exceeds 90°C.
- Power consumption of the collector loop pump is 45 W during times of operation. The controller power consumption is 3 W at all times.
- There is no heat transferred from the collector loop pump to the collector loop fluid
- These modifications were implemented to make the results of the next sets of simulations more comparable.

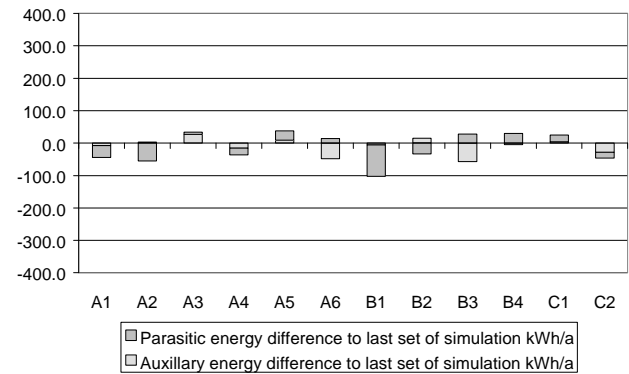
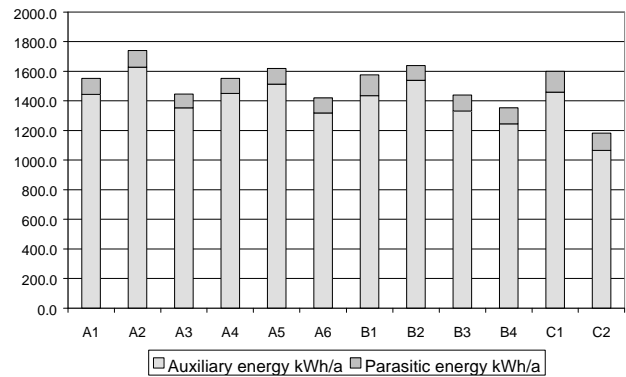


Figure 10: Third set of simulation results under the boundary conditions described above

The influence on auxiliary energy of the changed system configuration is rather small. The only remarkable decrease in auxiliary energy for systems A_6 and B_3 is caused by the increased overheating temperature from 65°C to 90°C.

The strong decrease on parasitic energy for system B_1 may be explained by the reduced pump power consumption from 85 to 45 W.

Set-up for the fourth set of simulations

The set-up for the fourth set of simulations is based on the set-up for the third set of simulations. The only modifications made are: replacing the system-specific collector loop piping with a piping which is identical for all the systems. All collector loop piping has an inner diameter of 10 mm and is insulated according to the state of the art. The pipe lengths are identical in all simulations: 5 m indoor, 8 m outdoor for feed and return lines each.

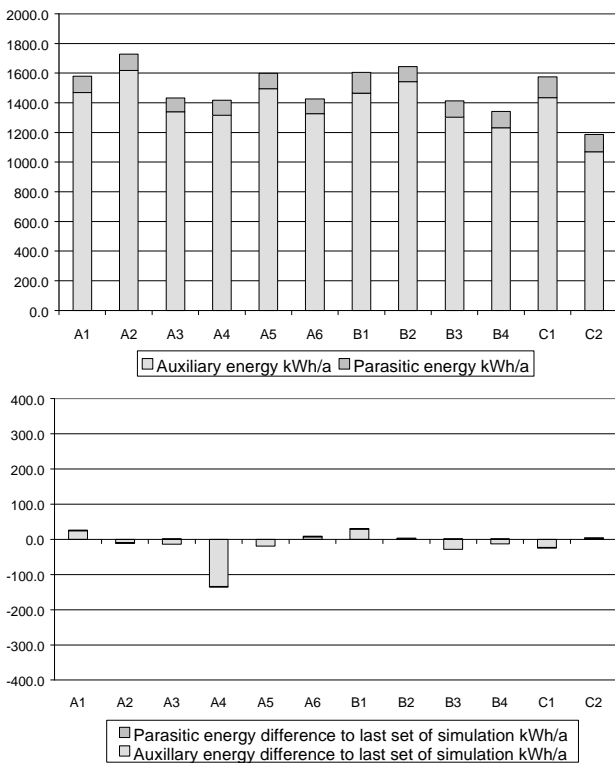


Figure 11: Fourth set of simulation results under the boundary conditions described above

Except for system A₄, the influence of replacing the piping is surprisingly small. Obviously one of the weak points of system A₄ was the insufficient piping insulation.

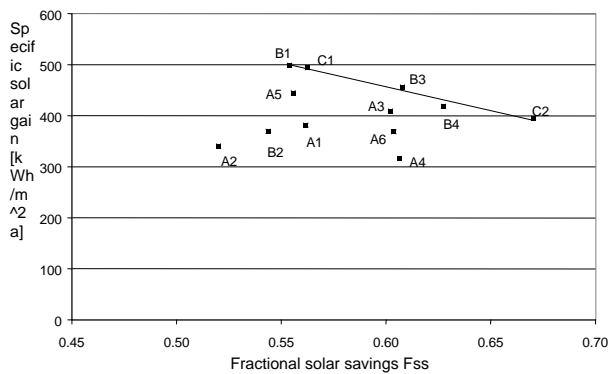


Figure 12: Solar fractional savings in relation to the specific solar gain (energy consumption reference system 3600 kWh/a) for the fourth set of simulations

Figure 12 shows a nearly linear dependence of the solar fractional savings to the specific solar gain of the systems B and C. An exception is System B₂ where especially the high storage losses cut down the performance. The difference in performance between the A and the other systems is clearly related to the main difference: enhanced stratification during the solar charging process.

Set-up for the fifth set of simulations

For the fourth set of simulations all systems were combined with the same collector field: 4 m² of flat plate collectors.

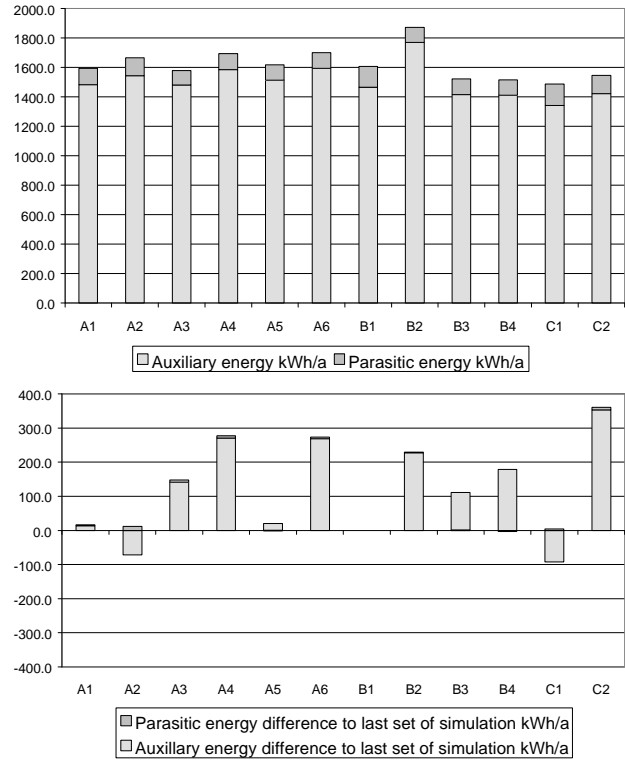


Figure 13: Fifth set of simulation results under the boundary conditions described above

As expected, systems with collector areas larger than 4 m² show an increase in auxiliary energy. This results show mainly the characteristics of the storage tank. The collector loop including piping is the same for every system. Of course still different is the flowrate in the collector loop. Except for system B₂, system performances are much more leveled out than in the first (as tested) simulation set-up.

Set-up for the sixth set of simulations

The last step in trying to make systems more comparable with respect to heat exchangers and flow type (low-flow versus traditional flow) the auxiliary volume is reduced to 150 l for each of the systems.

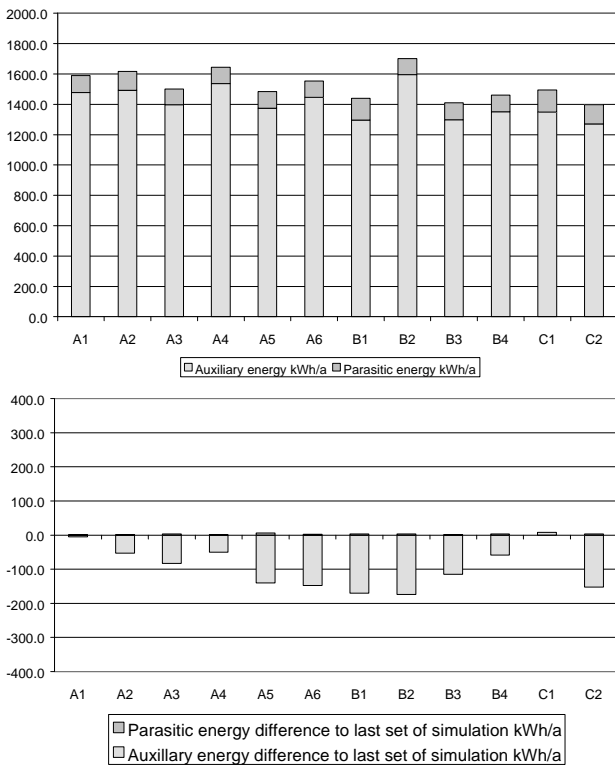


Figure 14: Sixth set of simulation under the boundary conditions described above.

Except for system B₂ the more advanced systems B and C need less auxiliary energy (-5 to 10%) compared to traditional systems A.

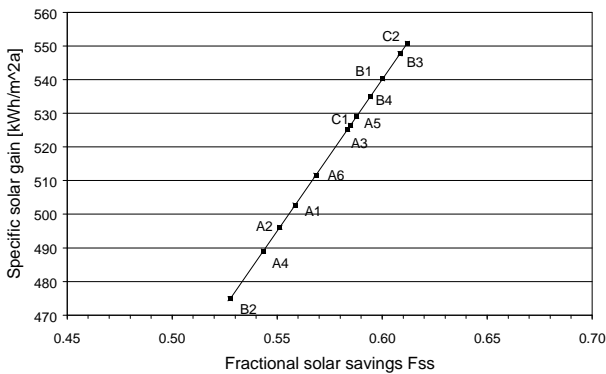


Figure 15: Solar fractional savings in relation to the specific solar gain (energy consumption reference system 3600 kWh/a) for the sixth set of simulations

In figure 15 it can be clearly recognized which systems perform better! The difference between the best (C₂) and the worst (B₂) system is about 20 % in performance. The advantage using low-flow coupled with high stratification in the storage tank is clearly demonstrated! Even using one high single heat exchanger (for example 40 % of the

storage height) using low-flow increases the system performance (A₅ and A₃).

5. CONCLUSIONS

The approach using results of component based system testing to investigate pros and cons of different system concepts has been successfully demonstrated.

Varying boundary conditions is an efficient tool to improve the comparison of system design features.

Systems have to be optimized to achieve maximum fractional solar savings under the conditions of the country (region) they are used.

Under typical Swiss conditions the difference in performance of the 12 systems taken into consideration, is as high as 20 % (absolute) in fractional solar savings.

Using an advanced concept is *not* a guarantee for high performance; one design error – as seen in system C₁ under Swiss conditions – might lead to a drastic cut in performance.

Low-flow in the collector loop, including heat exchangers for improved stratification, is leading to systems with higher performance than traditional systems.

The highest performance is reached with a mantle tank using even the bottom and top part of the storage tank as heat exchanger (tank in tank system).

There is still a potential for further improvements, but of course related to the boundary conditions of the respective country.

6. REFERENCES

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