ANALYSIS OF HYDRAULIC DESIGN OPTIONS FOR MEDIUM-SIZED SOLAR COMBISYSTEMS

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1. Abstract

The hydraulic set-up of a typical solar combisystem consists of at least four hydraulic loops (solar, auxiliary heating, domestic hot water preparation and space heating loop). A huge variety of options exist for the design of each loop and the interconnection of the loops. The objective of this investigation was to find recommendations for the selection of an appropriate hydraulic design for solar combisystems that allows the highest possible energy savings, depending on the specific boundary conditions of a heating system. First, a market analysis was carried out to identify and analyze all possible options. After that annual system simulations were performed for the most promising options. Based on these results two alternative design options are proposed, one for the integration of unpressurized storages and one for storages operated under pressure. In focus are medium-sized solar combisystems for one- and two-family houses with a collector area of more than 15 m² and a storage volume of more than 2 m³.

2. Introduction

The hydraulic set-up of a typical solar thermal combisystem consists of at least four hydraulic loops. A hydraulic loop comprises of a heat source and a heat sink (Schramek, 2007). The four loops are: the solar, the auxiliary heating, the domestic hot water (DHW) preparation and the space heating (SH) loop (see fig. 1).

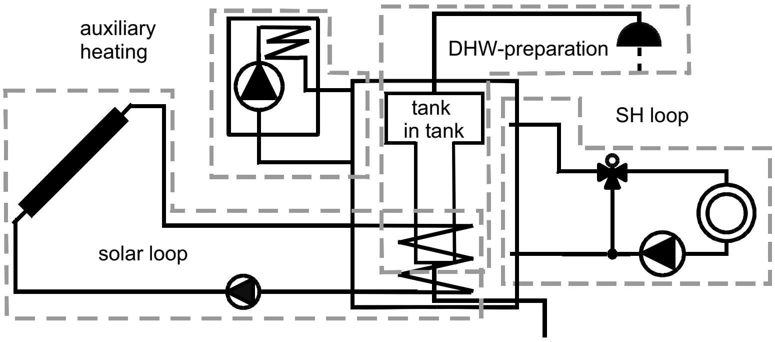


Fig. 1: Example for the hydraulic design of a small solar thermal combisystem

A huge variety of options exist to interconnect the hydraulic components and loops of a solar thermal combisystem. This paper aims to give guidance on the selection of an appropriate hydraulic design that allows the highest possible energy savings, depending on the specific boundary conditions of a heating system. In a first step, a market analysis was carried out in order to get an overview of these, often very complex, hydraulic schemes. This analysis revealed that the design of each hydraulic loop in a solar thermal combisystem can be characterized by the following four main features:

1. The realization of the charge and discharge process (with or without stratification devices, with internal or external stratification devices).
2. The integration of the heat storage (with or without additional heat exchanger for operation as unpressurized storage).
3. The type of heat exchangers that are used (external plate heat exchanger or internal coiled tube heat exchanger).
4. The integration of the auxiliary heating (via auxiliary volume or increase of the return flow temperature).

In a next step, typical hydraulic schemes for each loop were identified and the specific boundary conditions were defined and described. The option to integrate the auxiliary heater via increase of the return flow temperature was not part of the investigation. Only auxiliary heating via an internal auxiliary volume in the storage is considered within this paper.

Subsequently, annual system simulations were performed for a selected number of design options in the simulation environment TRNSYS (Klein et al., 2009). The influence of the charge and discharge strategy (feature 1 in the list above) on the performance of a medium-sized solar thermal combisystem has already been discussed in previous work: (Zass, 2007 and 2008). There, the impact is discussed of external stratification devices (i.e. valves that allow the water to enter the storage in two different heights) and internal stratification devices (i.e. pipes with several holes placed inside the storage) on the fractional energy savings $f_{sav,ext}$. The details of these investigations are therefore not further explained in this paper. The same accounts for the influence of further parameters and system settings, like the settings of volume flow rates and set temperatures or the operation of a circulation line (see tab. 6).

Finally, based on these cumulated results, recommendations for the hydraulic design of medium-sized solar combisystems are made.

3. Analysis of hydraulic design options for the four hydraulic loops

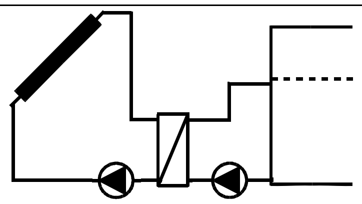
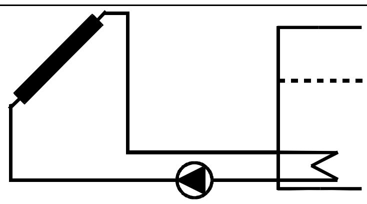
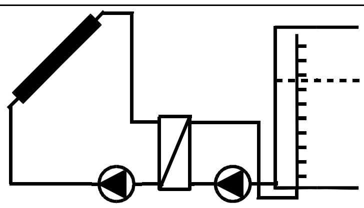
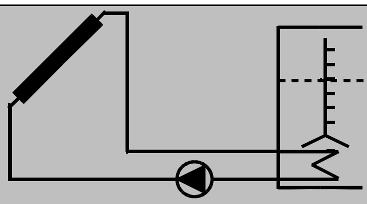
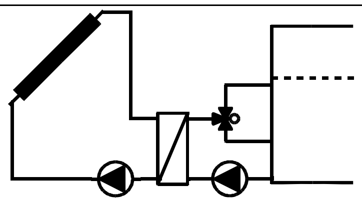
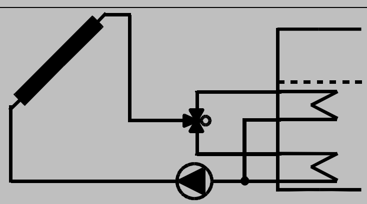
3.1. Solar loop

With the charge and discharge strategy, the integration of the heat storage and the type of heat exchanger used, three main differences in the design of a hydraulic loop for solar thermal combisystems were identified. In case of the solar loop, the integration of the heat storage is usually done via a heat exchanger. This is needed for the separation of the collector fluid and the water in the storage. For the solar loop design it does not matter whether the storage is operated under pressure or not.

Collectors that are filled with water without the addition of an antifreeze mixture are also technically feasible. The frost protection can then be realized by draining (Drain-Back-System) or by heating the collector loop in winter. Then, a heat exchanger is not needed. However, the use of water in the collector loop still poses technical challenges for components and controllers and is so far only a niche product in Central Europe.

In total six different hydraulic design options for the solar loop were identified (see tab. 1), when combining the different possibilities for charging and discharging (with internal or external stratification devices) with the different types of heat exchangers (internal or external).

Tab. 1: Hydraulic design options for the solar loop (only options with heat exchanger, the grey options are not considered)

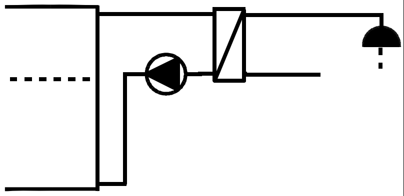
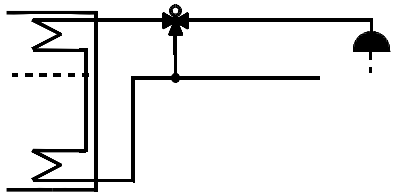
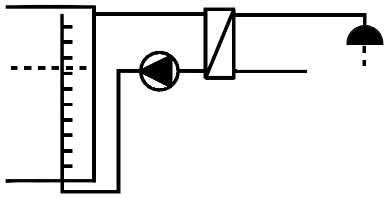
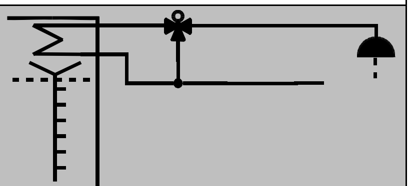
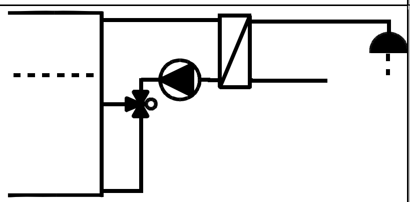
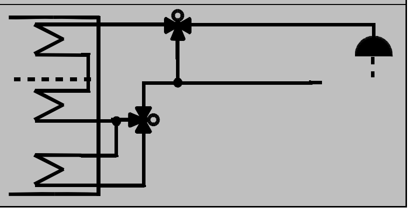
type of heat exchanger → charge strategy ↓	a) external heat exchanger	b) internal heat exchanger
1. without stratification device		
2. internal stratification device		
3. external stratification device		

The use of an external stratification valve to switch between two internal heat exchangers that are installed in different heights is very complex and costly. This option was therefore not part of the following simulation study. The option with an internal stratification device with internal heat exchanger was also not simulated. Previous investigations (Jordan and Vajen, 2002a, 2002b and Lorenz et al., 2000) have already shown that internal stratification devices have a similar influence on the fractional energy savings for internal as well as for external heat exchangers. Therefore, the results of the variants with external heat exchanger, with and without stratification devices, already indicate which improvements are feasible for internal heat exchangers.

3.2. DHW preparation

As for the solar loop, the combination of the different possibilities for charging and discharging and the type of heat exchanger used results in six hydraulic design options for the DHW preparation (see tab. 2). The option with internal heat exchanger and external stratification device (3b in tab. 2) is rather expensive and cannot be found on the market. This option was not simulated, as well as an internal heat exchanger and internal stratification device (2b in tab. 2). For the option 2b is assumed that, as for the solar loop, the influence of the discharge strategy on the fractional energy savings is the same for internal and external heat exchanger.

Tab. 2: Hydraulic design options for the DHW preparation (only options with heat exchanger, grey options are not considered)

type of heat exchanger → **discharge strategy ↓**	**a) external heat exchanger**	**b) internal heat exchanger**
1. without stratification device		
2. internal stratification device		
3. external stratification device		

Systems with a large hot water demand are often equipped with an additional DHW-storage. This is not only used as auxiliary volume but also provides a constant hot water temperature.

For small as well as for large systems, the on-demand DHW preparation via external heat exchanger units (so called hot water preparation units) were more and more in demand for the last years.

In a German market review from 2010 (Meyer, 2010) 46 suppliers of hot water preparation units for single- und multi-family houses were listed. Two years earlier (Meyer, 2008), there were only 22. Compared to DHW-storages and internal tube heat exchangers, these hot water preparation units only have a very small volume of stored hot water and thus ensure a hygienic hot water preparation.

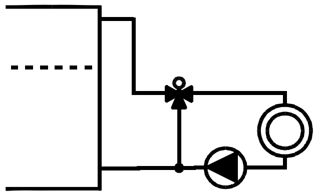
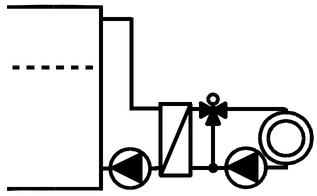
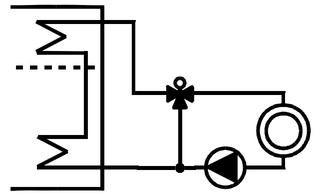
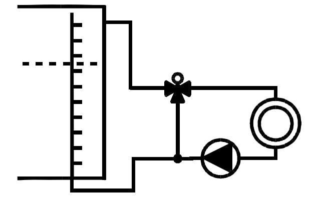
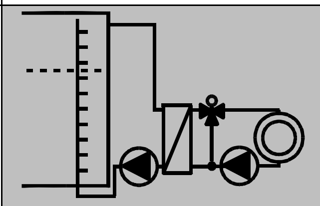
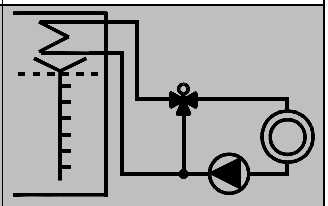
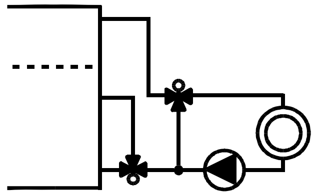
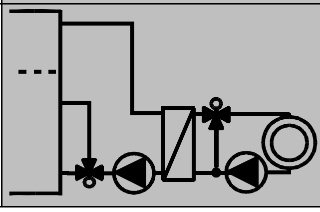
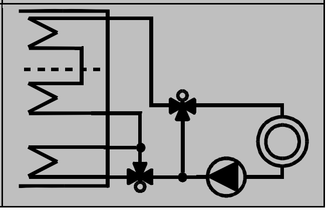
The control of the hot water temperature is either realized by mixing of the return flow with the forward flow from the storage or with the aid of a modulating pump which adapts the flow rate on the primary side. A modulating pump was used for the simulations here. With an internal heat exchanger the control can only be realized by mixing the return flow to the forward flow with the aid of a thermostatic mixing valve (see tab. 2, right column).

3.3. Space heating loop

Other than for the solar loop and the DHW preparation, the SH loop is usually directly connected to a storage without the use of a heat exchanger. This is possible as long as the storage is operated under pressure. When integrating an unpressurized storage or a floor heating system, a heat exchanger is required to separate the different pressure levels. In total, the combination with the different discharging strategies and the type of heat exchanger used gives 9 hydraulic design options for the SH loop (see. tab. 3).

Again it is assumed that the influence of the discharge strategy on the fractional energy savings is the same for internal and external heat exchanger. They are thus not taken into consideration for the following simulation study.

Tab. 3: Hydraulic design options for the SH loop (only options with heat exchanger, the grey options are not considered)

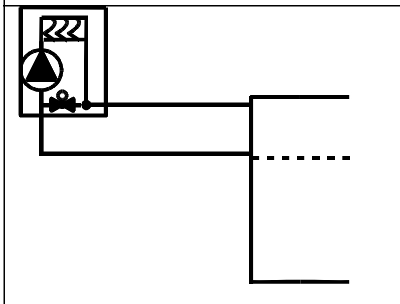
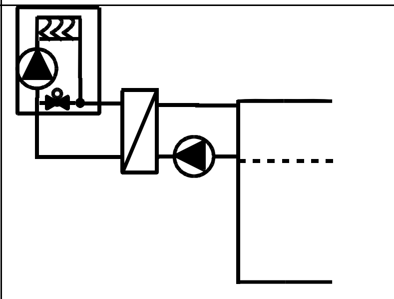
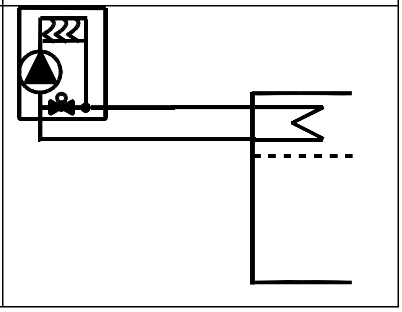
type of heat exchanger → / discharge strategy ↓	a) without heat exchanger	b) external heat exchanger	c) internal heat exchanger
1. without stratification device			
2. internal stratification device			
3. external stratification device			

3.4. Auxiliary heating

As for the SH loop, a heat exchanger is required to separate the different pressure levels in case the storage is unpressurized. This leads to three possible hydraulic design options for the auxiliary heating loop, depending on which type of heat exchanger is used, see tab. 4.

The implementation of a stratification device is not considered as being useful in the auxiliary heating loop. The charging of the auxiliary volume is usually done at a constant set temperature. With a stratification device, the forward flow would always enter the storage at the highest level. This can also be achieved with a fixed inlet.

Tab. 4: Hydraulic design options for the auxiliary heater integration

a) without heat exchanger	b) external heat exchanger	c) internal heat exchanger
		

4. System simulations

The annual system simulations described in the following were done with the simulation tool TRNSYS (Klein et al., 2009).

4.1. Definition of fractional energy savings

The parameter "extended fractional energy savings" ($f_{sav,ext}$) is used as an indicator for the performance of the solar thermal system. It was defined in the IEA-SHC Task 26 as the saved "combined total energy consumption of the solar combisystem" ($E_{total,solar}$), compared to the "combined total energy consumption of a reference system" without solar assistance ($E_{total,ref}$) (Weiss et al., 2003):

$$f_{sav,ext} = 1 - \frac{E_{total,solar}}{E_{total,ref}} \quad \text{...(eq. 1)}$$

This definition does not only take the auxiliary energy consumption of the systems into account, but also the parasitic energy consumption for pumps and controllers.

A medium-sized solar thermal combisystem for a single family house was defined as reference system for the investigations. All simulation results presented in the following are compared to the $f_{sav,ext}$ value of this reference system.

4.2. The reference solar thermal system

In order to achieve fractional energy savings of more than 30 %, a collector with 20 m² was combined with a storage of 3 m³. Typical hydraulic set-ups were selected for the four hydraulic loops of the reference solar thermal system according to the current state-of-the-art, which was defined within the frame of IEA-SHC Task 26 "Solar Combisystems" and Task 32 "Advanced Storage Concepts for Solar and Low Energy Buildings" (see fig. 2).

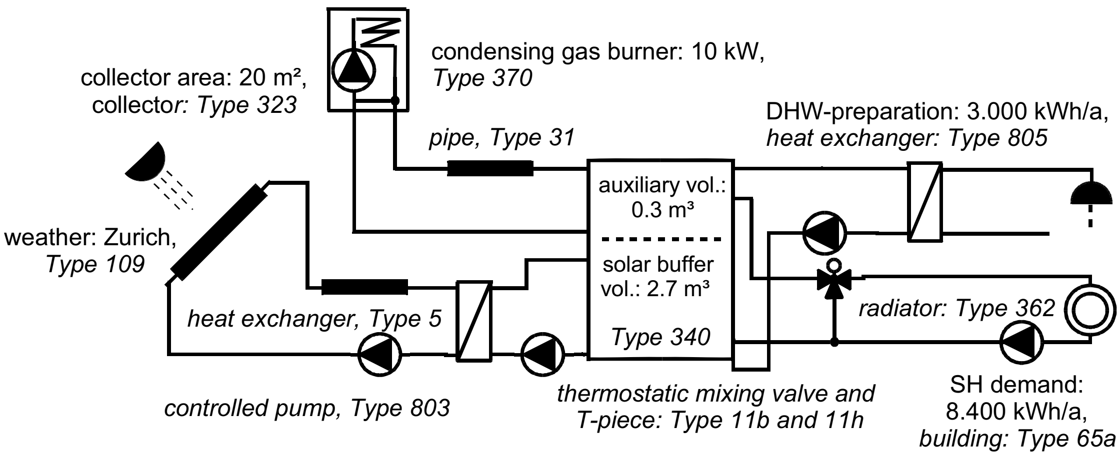


Fig. 2: Hydraulic design of the reference solar thermal system and the most relevant used TRNSYS-types

External heat exchangers are applied for both, the collector loop and domestic hot water preparation. A condensing gas burner is used as auxiliary heater. It heats an internal auxiliary volume of 0.3 m³. The heater is switched off during summer (from May to September) to avoid standby losses.

The controller settings, the hot water demand profile, the building model as well as the weather data file were also defined according to the recommendations of the IEA-SHC Tasks 26 and 32 or according to the state-of-the-art. Detailed information can be found in (Weiss et al., 2003, Hadorn, 2005 and Heimrath and Haller, 2007). The reference conditions and settings are summarized in tab. 5. The alternative values for varied parameters can be found in (tab. 6).

Tab. 5: Parameter settings and boundary conditions for the annual system simulations in TRNSYS.

collector area (aperture area)	20 m² (flat plate)
auxiliary volume	0,3 m³
storage volume	3 m³
UA-value storage	5,6 W/K
DHW demand (w/o circulation)	200 l/d
space heating demand	8.400 kWh/a
design temperatures for space heating	flow: 40°C/ return: 35°C (ambient temp. -10°C)
location	Zürich
orientation	South
collector tilt angle	45°
auxiliary heating	condensing gas burner, 10 kW
set temperature for DHW/ auxiliary heater	45°C/ 63°C
simulation time step	3 min
tolerances for integration/ convergence errors	0,03 % / 0,03 %

Tab. 6: Settings of varied parameters

Parameter	**reference conditions**	**alternative value**
design temperature for SH loop	40/35	55/35
specific flow rate in the collector loop in l/m²h	15	35
set temp. for hot water preparation/ auxiliary heater in °C	45/63	60/70
running time of circulation pump in h/day	0	8

4.3. Modelling of the internal and external heat exchangers

A capacity free counter flow heat exchanger was applied for the simulation of the external heat exchangers in TRNSYS (TRNSYS Type 5b, in Klein et al., 2009). The effectiveness of the heat exchanger and the resulting outlet temperatures are calculated with a given UA-value as well as inlet temperatures and mass flow rates as input values.

An adapted version of this heat exchanger model (described in Heimrath and Haller, 2007) was used for the DHW preparation. Here, the mass flow rate of the primary side is not an input but is calculated in an iterative process in dependence of the inlet temperatures and the mass flow on the secondary side, such that a given DHW outlet temperature on the secondary side is achieved.

UA-values as recommended in (Heimrath and Haller, 2007) were used for external heat exchangers for DHW preparation and solar loop. The dimensioning of the UA-values for the external heat exchangers in the SH loop and in the auxiliary heating are based on an average temperature difference of 5 K and the maximum required heating rates of 4.6 kW (SH loop) and 10 kW (auxiliary heating, values see tab. 7).

The respective function of the storage model according to (Drück, 2006) was used for the simulation of the internal heat exchangers. This model only allows for the integration of up to four internal heat exchangers, of which just two can be placed side by side in the same storage level. That is why the option with internal heat exchanger for the auxiliary heating loop was not simulated.

As for the external heat exchanger, the internal heat exchangers were modeled with constant UA-values. The dependence of mass flow and temperature was neglected. The same UA-values were assumed for internal and external heat exchangers. These values tend to be higher than actually needed, i.e. the heat exchangers are slightly oversized. Further calculations would be necessary for the optimal dimensioning of the heat exchangers. Also, for the internal tube heat exchangers it still needs to be verified whether the required tube lengths fit completely into the storage.

Tab. 7: Assumed UA-values for internal and external heat exchangers

	UA-value for external heat exchanger in W/K	UA-value for internal heat exchanger in W/K
Solar loop	2000	2000
DHW preparation	5300	5300
SH loop	1000	1000
Auxiliary heating	2000	-

4.4. Simulation Results

Annual system simulations were performed for the hydraulic design options described in chapter 3. Fig. 5 gives an overview of the results. It shows the difference of the $f_{sav,ext}$-values to the value of the reference solar thermal system ($f_{sav,ext}$ = 41.92 %).The results are divided into two groups, according to their parameter settings from tab. 6. In the upper part are shown the influence of the charge and discharge strategy (without, with internal or with external stratification devices) and the type of heat exchanger (without, with internal or with external heat exchangers) with parameter settings that are advantageous for the solar thermal system operation (column “reference conditions” in tab. 6). In the lower part the results with rather unfavourable parameter settings (column “alternative values” in tab. 6) are displayed. Moreover, the additional energy savings achieved by increasing the collector area by 2 m² and 4 m² are presented. They allow a better classification of the achieved results. Fig. 5 helps to illustrate the following conclusions and recommendations:

Influence of the charge and discharge process:

- With parameter settings that are advantageous for an efficient operation of a solar thermal combisystem, as is the case for the reference system, almost no increase in the fractional energy savings is possible by using internal or external stratification devices (less than 1 %-point, see first three rows in fig. 3 and rows 3 to 10 in fig. 5).
- The installation of stratification devices can limit the negative effect of unfavourable parameter settings on the fractional energy savings. Improvements of up to 3 %-points are possible with stratification devices in all loops (see last three rows in fig. 3). This confirms previous results from (Andersen and Furbo, 2007). The highest increase thanks to a single stratification device is achieved for a stratified discharge of the DHW preparation when the DHW set temperature is increased to 60°C and a circulation line is in operation ($\Delta f_{sav,ext}$ = 2 %-points, compare rows 29 and 33 in fig. 5).
- The internal stratification devices are modeled as ideal stratifiers. That means it is assumed that the inlet flow always enters the storage at the level with the same temperature. The $f_{sav,ext}$-values for the internal stratification devices are therefore at least as high as with external stratification devices. In reality the influence of the internal device will lie in between the results for the ideal stratification and the external stratification devices (as can be seen in fig. 3). When a stratification device shall be installed, an internal device should be preferred, not because of the slightly better performance but because it does not need to be actively controlled.

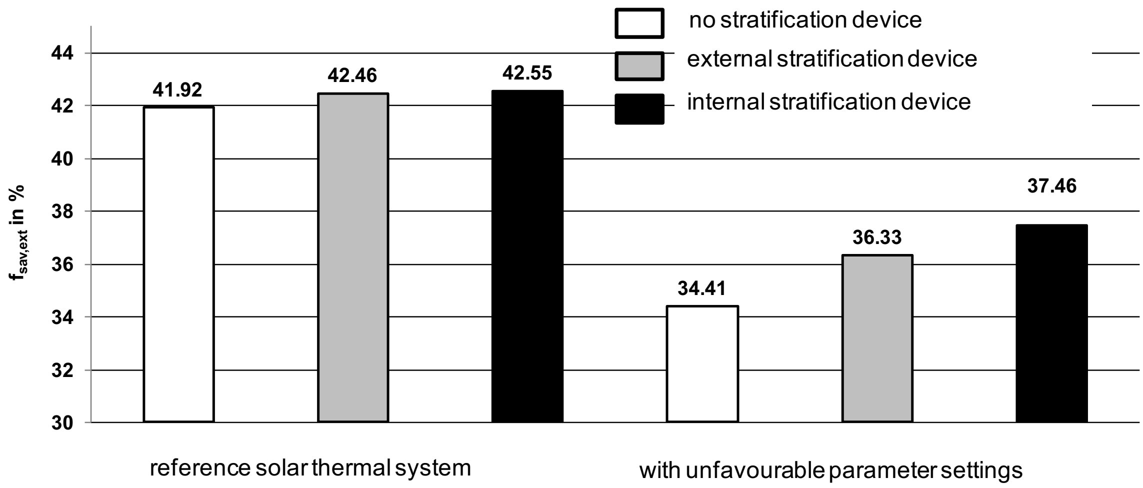


Fig. 3: Influence of the use of internal or external stratification devices in all loops on the fractional energy savings at reference conditions in tab. 6 (three rows on the left) and with unfavourable parameter settings ("alternative values" in tab. 6, three rows on the right).

Influence of heat storage integration and the type of heat exchangers used:

- Additional heat exchangers in the SH loop and in the auxiliary heating loop lead always to a decrease of the fractional energy savings. While the influence is small for only one additional heat exchanger (up to 3.3 %-points, rows 4, 5 and 8 in fig. 4, rows 11 to 15 in fig. 5), already considerable reductions have to be accepted with two additional heat exchangers (4.9 %-points for internal and 5.5 %-points for external heat exchangers, rows 2 and 3 in fig. 4 and rows 16 and 17 in fig. 5).
- When comparing the fractional energy savings for internal and external heat exchangers, the higher value is achieved with the internal heat exchanger in most cases (at the given UA-values). The reason for this is the additional pump that is required for the operation of the external heat exchanger units. This leads to an increased electricity consumption and thus to a reduction of the fractional energy savings. The difference between internal and external heat exchanger is the higher the longer is the running time of the pump. That is why the difference is negligible for the solar loop (rows 1 and 8 in fig. 4) but rather clear in the SH loop (rows 5 and 7 in fig. 4) and for the auxiliary heating (not in fig. 4).
- From this it could be concluded that the use of internal heat exchangers should always be preferred. However, there are further aspects that have not been considered yet. On the one hand internal tube heat exchangers cause higher pressure losses. This limits the maximum length that might be realized. On the other hand it has to be made sure that all internal heat exchangers for all loops fit completely into the storage. Both have to be checked individually during the planning process.

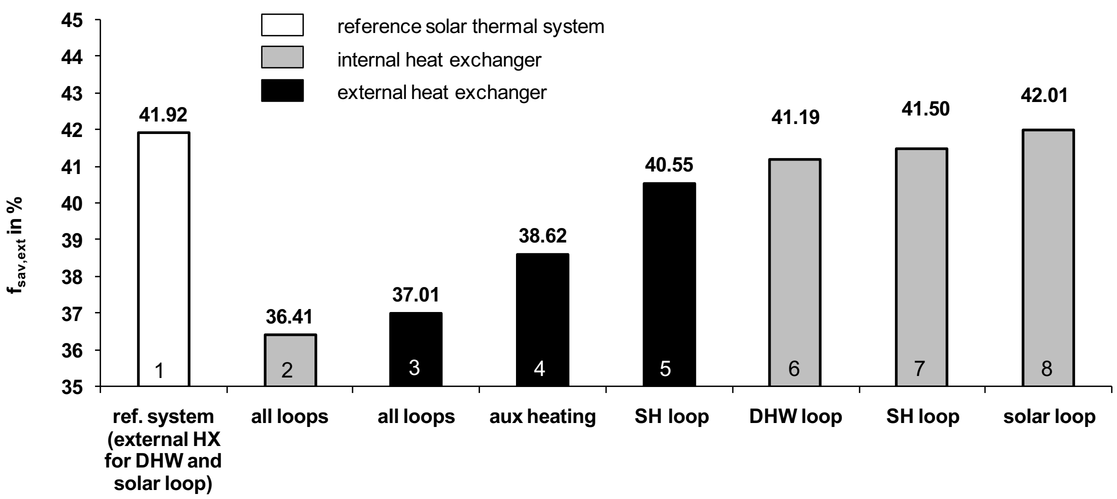


Fig. 4: Influence of the use of internal or external heat exchangers on the fractional energy savings.

Influence of varied parameter and system settings:

- In most cases the parameters from tab. 6 have a higher influence on the $f_{sav,ext}$-value than the choice of the hydraulic design option (here referred to the charge and discharge strategy and the type of heat exchanger installed, see rows 18 to 42 in fig. 5).
- If the influences mentioned up to now are compared to the additional savings achieved by increasing the collector area (1.6 %-points with 2 m² and 3 %-points with 4 m², see rows 1 and 2 in fig. 5) one can observe that this increase is slightly higher than detected for the use of stratification devices (0.6 %-points, see row 3 in fig. 5).

5. Summary and conclusions

Within this paper, the huge variety of design options for medium-sized solar combisystems was characterized according to the four main hydraulic features (realization of charge and discharge process, integration of heat storage, type of heat exchangers used and integration of the auxiliary heating). In a next step, the most promising options were analyzed with annual system simulations. The results can be summarized as follows:

- The influence of stratification devices on the energy savings is rather small for most of the investigated cases. The use of internal devices gives slightly higher savings than the use of external ones.
- The use of additional heat exchangers for operation of an unpressurized storage leads to a significant decrease in energy savings for the given UA-values. This effect can be mitigated by increasing the heat exchanger area and thus the UA-values.
- When comparing the fractional energy savings for internal and external heat exchangers, the higher value is achieved with the internal heat exchanger in most cases (at the given UA-values). The reason for this is the additional pump that is required for the operation of the external heat exchanger units.
- In most cases, changes of the external boundary conditions have a larger influence on the achievable energy savings than the hydraulic design features.

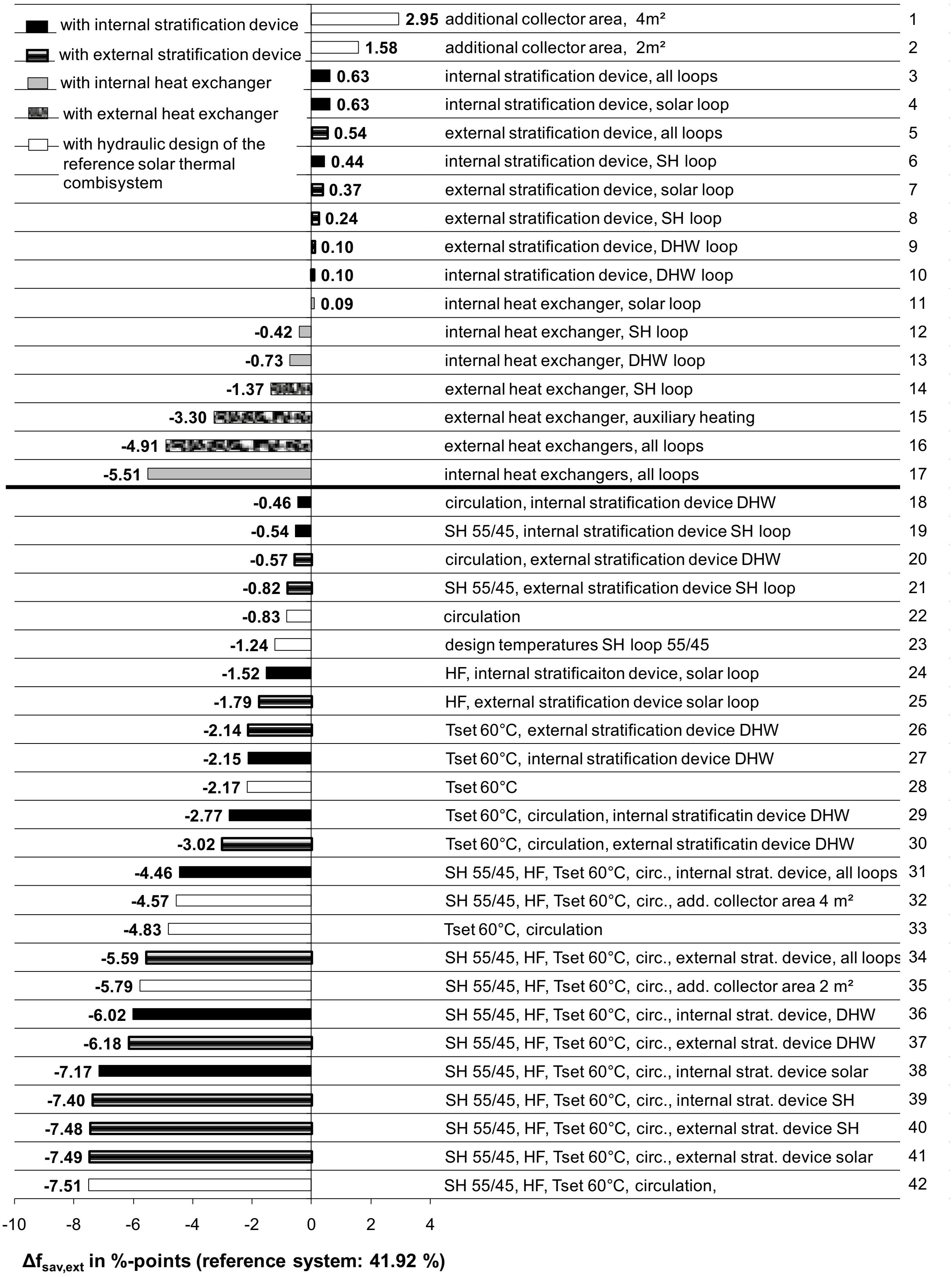
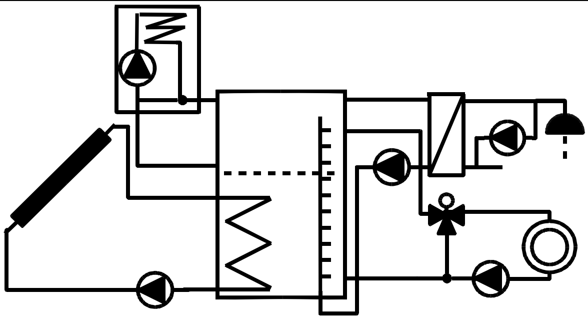
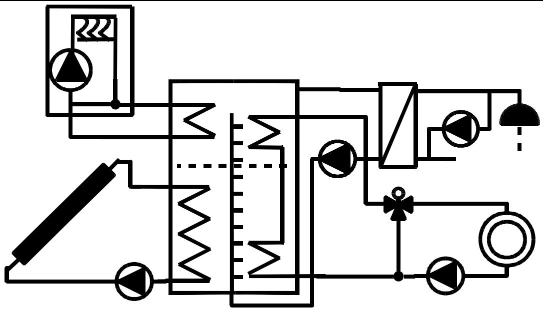


Fig. 5: Changes in $f_{sav,ext}$ compared to the $f_{sav,ext}$ –value of the reference solar thermal system for all described options. Upper part: with favourable parameter settings (column "reference conditions" in tab. 6), lower part: with unfavourable parameter settings (column "alternative values" in tab. 6). HF – high flow, circ. – circulation, strat. – stratification.

Based on these results, a list of recommendations for the hydraulic design of medium-sized solar combisystems is finally derived. In tab. 8 two alternative design options are proposed, one for the integration of unpressurized storages and one for storages operated under pressure. Except for the DHW-preparation, the use of internal heat exchangers is recommended, because of the better results compared to the external heat exchangers. For the DHW-preparation a hygienic, fast and reliable supply at a constant temperature is crucial. That is why an external heat exchanger is recommended. For the dimensioning of the internal heat exchangers further aspects like the higher pressure loss and the maximum heat exchanger length that fits into the storage have to be taken into account. The use of a stratification device is recommended when operating a circulation line. It should be connected to the storage via a separate heat exchanger if the circulation line is operated more than the assumed 8 h per day (Peuser et al., 2008).

Tab. 8: Recommendations for the choice of a hydraulic design.

storage operated under pressure	unpressurized storage
	
- internal heat exchanger solar loop, - internal (or external) stratification device for DHW return flow when operating a circulation line.	- internal heat exchanger in solar loop, SH loop, auxiliary heating - external heat exchanger for DHW preparation - internal (or external) stratification device for DHW return flow when operating a circulation line.

6. Acknowledgements

The presented investigations were carried out within the frame of one completed ("Development of Modular and Compact Charge and Discharge Units for Large Combined Storages", FKZ 0327390B, Vajen et al., 2009) and one current research project ("Investigations on Simple and Inexpensive Charge and Discharge Systems for Large Hot Water Storages", FKZ 03ET1006A). The authors acknowledge the support of these projects by the German Federal Ministry of Economics and Technology (BMWI) and by the company Wagner & Co Solartechnik GmbH.

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