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Simulation and evaluation of different boiler implementations and configurations in solar thermal combi systems

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Abstract

This simulation study investigates both different boiler specifications and various kinds of boiler integration in solar thermal combi systems with the help of a new developed fossil fuel boiler model. For each variant, the simulation outcomes to be discussed are the annual boiler efficiency, the cycling rate and, as the main indicator, the primary energy savings of the complete system. The results indicate that the effects of a solar thermal system on the annual boiler efficiency are small. Besides the system layout the annual amounts of hot water and space heating demand and their temperature levels affect the impact of the solar thermal system. Each additional storage tank, which is heated by conventional energy, should be analyzed critically due to their additional heat losses, which reduce the system efficiency. The latter is particularly true for a boiler buffer storage. This study points out that the savings of primary and final energy are the most important indicators for the assessment of solar thermal combi systems. Subsystem indicators like the annual values of collector yield and boiler efficiency give additional information, but they are not sufficient for a full evaluation of a complete system.

Keywords: Solar thermal combi systems; boiler; interconnection; buffer storage; boiler model

1. Introduction

Solar thermal combi-systems may contribute significantly to domestic hot water preparation and space heating demand. Conventional boilers often provide the remaining energy demand in these systems.

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Therefore, the proper interconnection of both heat sources is of highest importance. The main indicator is final energy use, which has to be minimized, while the amount of primary energy use has to be regarded, too. For the subsystems, the collector yield and the boiler efficiency have a high significance. Solar heat gains, however, influence the boiler efficiency. For example, solar heat may lead to higher boiler return temperatures and therefore reduce condensation effects or the solar heat forces the boiler to operate more often in partial load conditions, both possibly reducing primary energy savings. On the other hand, the standby heat losses of the boiler may be reduced if the heat load is fully covered by the solar thermal system.

Several authors analyzed the integration of boilers in conventional heat supply systems (e.g. [1]). Other studies investigated the optimization of solar thermal combi systems; a part of them also discussed the proper pellet boiler integration in the system (e.g. [2]). However, there is no study published yet, which gives a detailed evaluation of solar thermal combi systems, with focuses on the optimum boiler characteristics and the optimal way of integrating the boiler into the system.

This paper discusses different variants of solar thermal combi systems with gas or oil boilers as conventional heat generators. A simulation study has been performed using TRNSYS, in which a new fossil fuel boiler model has been applied. This model has been developed with particular regard to the condensation heat gains and the dynamic behavior including the start-up stage using parameters, which are easily to be obtained [3].

Nomenclature

f_{Sav}	fractional energy savings (-)
η_B	boiler efficiency (-)
H_{SFuel}	calorific value of fuel (kWh/kg)
m_{Fuel}	mass of fuel (kg)
Q_B	annual heat amount transferred from the boiler to the water circuit (MWh/a)
Q_{Fuel}	annual energy demand of boiler (MWh/a)
W_{el}	annual electricity demand (MWh/a)

2. System configuration and variants

The following system schemes of solar thermal combi systems comprise different hydraulic connections of the solar thermal collector and the boiler. Figure 1 shows the principles of the four basic configurations (variants) under discussion.

In variant 1, the solar heat is stored in a solar buffer storage, which is connected to the return of the heating system. The return may be pre-heated by the solar buffer storage and heated up to the desired set temperature by the boiler afterwards. If the buffer temperature is above the set temperature, the system operates without the boiler (bypass before boiler). The domestic hot water (DHW) is prepared and stored in a small DHW tank.

Variant 2 includes an additional boiler buffer storage, which is installed in parallel between boiler and heating network. Variant 3 integrates the solar and boiler buffers in one (larger) storage tank. Either a DHW tank (variant 3a) or an external heat exchanger (fresh water module, variant 3b) serve for the domestic hot water preparation. An improvement of the stratification within the storage may lead to higher energy savings, especially in a larger storage tank [9]. Such an improvement is realized in variant 3b using an ideal stratification device for the collector inlet on the one hand and two outlets for the space heating circuit on the other hand, which enable a stratified discharging in combination with a four way valve.

Boiler and solar buffer are connected in parallel in variant 4. A four-way valve directs the return mass flow to both components, where the distribution is depending on return, storage and set temperature. The motivation for this scheme is that the boiler may be operated in its optimum condition, because it receives the lowest possible return temperature and not a pre-heated mass flow. This seems to be advantageous, as the inlet temperature mainly affects the boiler efficiency, but the outlet temperature has only a marginal effect.

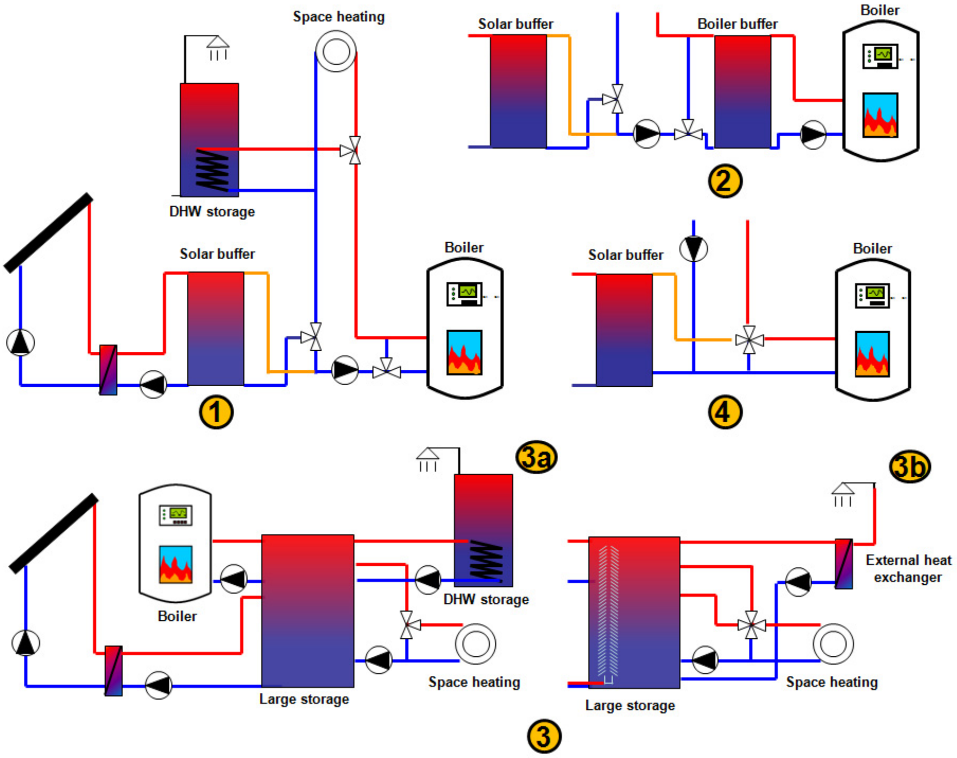

Fig. 1. Simulation variants of solar thermal combi systems

These four variants are simulated in TRNSYS [4]. The heat load is defined by a single family house at the location of Zürich, the data is taken from IEA SHC Task 26 and 32 [5]. Further boundary conditions for the simulations can be taken from Table 1. Besides the system parameters the table also lists the simulation models of the main components. For simulation the steady state and dynamic behavior of the boiler, a new model developed at ISFH is used. Table 1 also contains the boiler model parameters, which define its condensation and the dynamic behavior for a typical modulating gas boiler. More details about the model and its parameters can be taken from the model documentation [3].

Table 1. Simulation parameters and main component models

Collector (Type 832), Version 3.07 [6]	
Type	Selective flat plate collector
Area, slope, azimuth	0 m^2 / 8 m^2 / 15 m^2 / 30 m^2; tilt 45°, south
Conversion factor	0.80
Heat loss	$3.50 + 0.015 \cdot \Delta t$ (W/m^{2}K)
Collector mass flow rate	30 kg/m^{2}h
Storage tank (Type 340), Version 1.99F [7]	
Specific volume of solar buffer storage (Variants 1,2,4)	60 l/m^2 collector area
Volume of boiler buffer storage (Variant 2)	50 l
Volume of hot water storage (Variants 1,2,3a,4)	150 l
Volume of large storage (Variant 3)	60 l/m^2 collector area + 50 l auxiliary volume
Heat transfer capacity of heat exchanger (hex) for hot water preparation (internal hex in variant 3a, external hex in variant 3b)	1 kW/K (internal hex in hot water tank) 5.3 kW/K (external hex)
Insulation	0.035 W/mK, 0,1 m thick
Additional heat losses of thermal bridges and tube internal recirculation losses	Each port +0.1 W/K, +20% (according [8])
Gas condensing boiler (Type 204), Version 1.1 [3]	
Modulating range	2.1 – 10 kW
Boiler and combustion efficiency at nominal heat load and test conditions according EN 303-3	95.5% / 97.7% (related to the lower calorific value)
Condensation parameters (Flue gas moisture at nominal heat and 35°C inlet temperature/dependence on heat load and inlet temperature)	100% / 0%/kW / 0%/K
Boiler water content / boiler mass	2.5 l / 46 kg
Pre purge/post purge time	20 s / 0 s
Dynamic characterization factors (portion of mass in gas-side capacity, portion of complete mass and water content in water-side capacity, portion of water content in dead band)	0.01 / 0.5 / 0.5
Control hysteresis (Switch on/off temperature difference)	±5 K
Heat demand	
Annual heat load (demand) for space heating	9 MWh/a (60 kWh/m^{2}a)
Design flow/return temperature and mass flow at design ambient temperature	40°C / 35°C / 794 kg/h
Hot water demand (no circulation)	200 l/day (45°C), i.e. 3 MWh/a

The storage tanks are located outside of the heated building envelope. Hence the storage losses during the heating period are no internal gains. The simulation time step is set to 1 minute, the internal time step of the boiler (Type 204) is set to 1 second, in order to reproduce the highly dynamic boiler behavior and its complex start and stop procedure. Each variant is evaluated using the annual boiler efficiency, which is related to the upper calorific value (see Eq. (1)).

$$\eta_{B,annual} = \frac{Q_B}{Q_{Fuel}} = \frac{Q_B}{m_{Fuel} \cdot H_{S,Fuel}} \qquad (1)$$

Furthermore, the fractional final energy savings are calculated according to Eq. (2) [5], which compare the energy demand of each system to a reference system. The reference system corresponds to variant 1 without solar thermal collectors and buffer storage.

$$f_{Sav} = 1 - \frac{\left(Q_{Fuel} + \frac{W_{el}}{0.4}\right)}{\left(Q_{Fuel} + \frac{W_{el}}{0.4}\right)_{Reference}} \qquad (2)$$

3. Results

3.1. Effect of the solar thermal system on the boiler performance in variant 1

Table 2 presents the simulation results for variant 1 at different collector areas.

Table 2. Simulation results of variant 1

Variant 1 collector area	0 m²	8 m²	15 m²	30 m²
Heat demand (including heat losses of hot water storage)	12590 kWh/a	12590 kWh/a	12590 kWh/a	12590 kWh/a
Final energy demand (gas)	13730 kWh/a	11247 kWh/a	9890 kWh/a	8005 kWh/a
Electrical energy demand	544 kWh/a	653 kWh/a	636 kWh/a	624 kWh/a
Collector yield	0 kWh/a	3298 kWh/a	4997 kWh/a	7490 kWh/a
Fractional final energy savings (Eq. 2)	0.0%	14.6%	23.9%	36.6%
Annual boiler efficiency	91.7%	91.6%	91.7%	91.3%
Boiler operation time	3552 h/a	2930 h/a	2539 h/a	1969 h/a
Boiler operation time for DHW preparation	376 h/a	285 h/a	247 h/a	210 h/a
Operation time of solar buffer	0 h/a	1485 h/a	2021 h/a	2787 h/a
Simultaneous operation of boiler and solar buffer	0 h/a	97 h/a	92 h/a	87 h/a
Annual number of boiler cycles	11059 1/a	5288 1/a	3630 1/a	2341 1/a
Average operation time of boiler (during one cycle)	19.3 min	33.2 min	42.0 min	50.5 min
Average boiler inlet temperature (energetic weighted))	33.3°C	33.4°C	33.6°C	34.3°C
Average boiler inlet temperature during operation of solar buffer (energetic weighted)	33.3°C	48.9°C	47.8°C	47.1°C
Condensate mass	1153 kg/a	957 kg/a	839 kg/a	661 kg/a
Specific condensate mass per kWh boiler output	83.9 g/kWh	85.1 g/kWh	84.8 g/kWh	82.6 g/kWh

The results show the effects of the solar thermal system on the boiler performance in variant 1:

- The solar thermal system has no significant effect on the boiler efficiency. The efficiency is almost constant between 0 and 15 m² and decreases by 0.4% at 30 m².
- A negative effect of the solar heat can be seen by the increasing boiler inlet temperatures (more than 10 K) at simultaneous operation of boiler and solar buffer storage. This leads to a lower boiler efficiency. However, the simultaneous operation occurs rather seldom (below 5% of the overall operation time of the boiler). The reason for this clarifying result is, that in most cases the buffer storage temperature either below the return temperature (boiler only) or above the desired set temperature (solar only, i.e. DHW preparation during summer or space heating in spring or autumn).

- A positive effect caused by the solar heat arises from the decreasing boiler operation time for hot water preparation (more than 40% at 30 m² collector area), when the boiler normally would operate at a higher temperature level. Over one year, the average boiler inlet temperature is only slightly increased (by max. 1 K).
- The solar thermal system reduces the operation time and number of boiler cycles and increases the average duration of one operation cycle. Due to the reduced gas consumption, the total condensate mass decreases. However, the specific condensation mass is almost constant (change below ±2%). This shows again, that the solar system affects only slightly the energy efficient boiler operation.

Summarizing the results for variant 1, the effects of the solar thermal system on the boiler operation are small. The positive effect of reduced operation time for DHW preparation and the negative effect of a higher boiler inlet temperature during simultaneous operation are approximately compensating each other.

3.2. Effects of a buffer storage

Figure 2 gives the number of boiler cycles, the collector yield and the annual final energy demand for the variants 1 to 3 at 30 m² collector area. Besides the modulating boiler according to Table 1, the simulations are repeated for each variant with a one-stage burner, while the other characteristics remain unchanged.

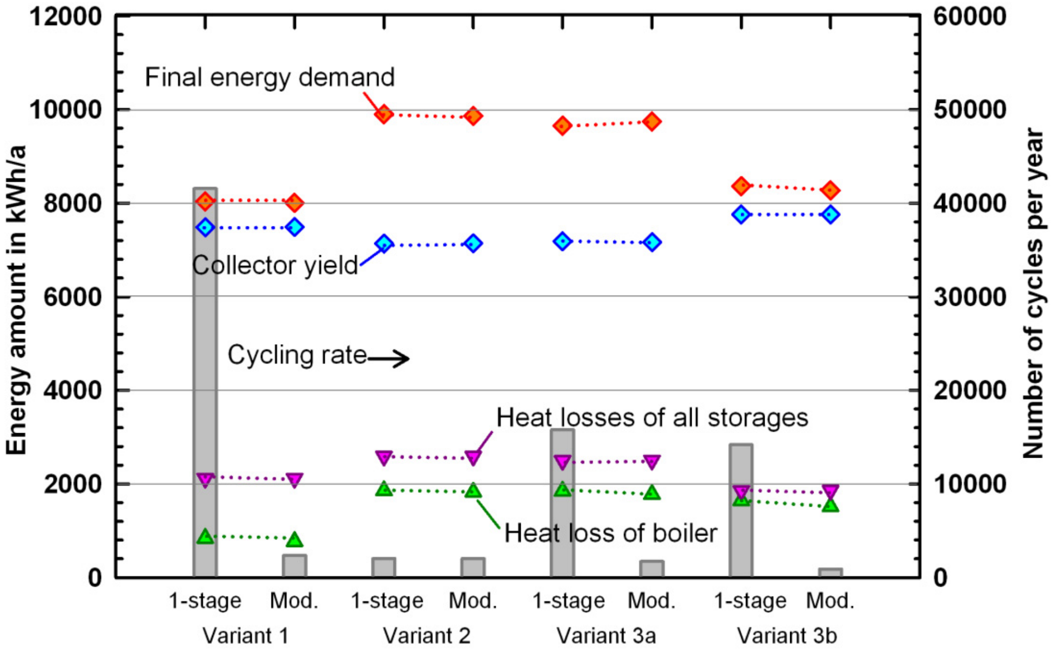

Fig. 2. Final energy demand, collector yield, heat losses of boiler and storages and number of boiler cycles for the variants 1 to 3 (collector area 30 m²)

Figure 2 shows the following results:

- The energy demand is smallest in variants 1 and 3b. In variant 1, the boiler efficiency is high and the boiler heat losses to the ambient air are small due to the lowest temperature level within the boiler (average inlet temperature about 34°C). The buffer storage unit in variant 3b leads to increasing boiler heat losses but decreasing storage heat losses (no hot water tank in contrast to variants 1 and 2). The stratified charging and discharging devices in variant 3b (see Section 2) also contribute to the final energy demand reduction with a portion of about 500 kWh/a, which is roughly one third of the difference between the variants 3a and 3b.
- The boiler buffer storage in variant 2 reduces the cycling rate of the one-stage boiler considerably, while in case of a modulating burner there is hardly a difference. In contrast, the energy demand increases significantly due to the additional tank losses and reduced boiler efficiency (average inlet temperature is 43°C).
- The storage heat losses of the bivalent storage in variant 3a are marginally smaller than in variant 2 with two buffer storages. The tank loss reduction is more pronounced in variant 3b with no hot water storage. Moreover, the higher capacity rate of the external heat exchanger (see Table 2) lowers the return temperature from the heat exchanger (primary side). This allows connecting the return pipe at the storage tank bottom, which decreases the collector inlet temperatur and thus increases the collector yield.
- A modulating burner decreases the number of boiler cycles especially in variant 1 with no buffer storage unit. Only 900 boiler cycles occur in variant 3b, the average operation time of the boiler is about 2 hours.

It has to be noted that the performance of variant 2 may be improved, if the boiler buffer storage is only used for the space heating demand. This would reduce the temperature level within the storage. Likewise an improvement may be expected if the hot water storage in variant 2 is replaced by an external heat exchanger (fresh water module) like in variant 3b. Furthermore, it may be possible to integrate a boiler with a larger water content, so that the boiler buffer storage is no more necessary.

3.3. Parallel connection of boiler and solar buffer storage (variant 4)

In contrast to the variants 1 – to 3, variant 4 shows a scheme, where the boiler and solar buffer storage are connected in parallel. This guarantees that the boiler always receives the system return temperature also in the case of simultaneous operation of both components. This happens when the buffer storage temperature is above the return temperature but below the set temperature. In this case the boiler outlet temperature has to be higher than the desired set temperature of the supply pipe, in order to allow a significant mass flow rate through the solar buffer storage. This may be realized using a constant set temperature or by defining a temperature difference, which will be added to the supply pipe set temperature. Table 3 compares the results of variant 1 and variant 4 with boiler set (outlet) temperatures during the periods of simultaneous operation.

Table 3. Simulation results of variant 1 and 4 at different boiler outlet temperatures during simultaneous operation (constant temperature or constant temperature difference added to the desired supply pipe temperature (demand temperature), collector area 30 m²)

	Variant 1	Variant 4			
		constant 63°C	constant 70°C	+10 K	+20 K
Final energy demand (gas)	8005 kWh/a	7990 kWh/a	8020 kWh/a	8077 kWh/a	8066 kWh/a
Electrical energy demand	624 kWh/a	624 kWh/a	624 kWh/a	623 kWh/a	624 kWh/a
Collector yield	7490 kWh/a	7505 kWh/a	7509 kWh/a	7415 kWh/a	7440 kWh/a
Heat from solar buffer	5329 kWh/a	5349 kWh/a	5351 kWh/a	5239 kWh/a	5270 kWh/a
Fractional energy savings	36.6%	36.7%	36.5%	36.1%	36.2%
Annual efficiency of boiler	91.3%	91.1%	90.7%	91.2%	91.0%
Operation time of boiler	1969 h/a	2065 h/a	2082 h/a	1998 h/a	2011 h/a
Operation time of boiler for hot water preparation	210 h/a	214 h/a	224 h/a	215 h/a	211 h/a
Operation time of solar buffer	2787 h/a	2840 h/a	2833 h/a	2920 h/a	2885 h/a
Simultaneous operation of boiler and solar	87 h/a	263 h/a	277 h/a	259 h/a	246 h/a
Boiler cycles	2341	4800	4824	3937	4233
Average operation time of boiler	50.5 min	25.8 min	25.9 min	30.4 min	28.5 min
Average boiler inlet temperature (energetic weighted)	34.3 °C	33.4 °C	33.4 °C	33.7 °C	33.6 °C
Average boiler inlet temperature during operation of solar buffer (energetic weighted)	45.7 °C	27.5 °C	28.1 °C	34.4 °C	34.0 °C

The results shown in Table 3 indicate that the parallel connection of solar buffer and boiler does not lead to significant improvements:

- The essential difference of variant 4 compared to variant 1 is the considerably lower boiler inlet temperatures during periods of simultaneous operation. Although the simultaneous operation time over one year is about three times higher than in variant 1, the reduction of the average boiler inlet temperature is less than 1 K. This shows, that simultaneous operation remains a rather seldom event.
- The boiler efficiency during simultaneous operation increases due to the lower inlet temperatures. However, the effect on the annual efficiency is small. In contrast, the number of boiler cycles is doubled and the operation time of the boiler increases both leading to higher boiler heat losses (increase by 5%) and lower annual efficiencies.
- Depending on the boiler set temperature at simultaneous operation the final energy demand slightly decreases or increases. A more intelligent control strategy considering the boiler outlet temperature might lead to higher energy savings. However, high improvements are not to be expected.

4. Conclusions

Figure 3 gives the fractional energy savings and the annual boiler efficiencies for all variants at different collector areas. The values for variant 4 corresponds to the best version with a constant boiler set temperature of 63°C during simultaneous operation (see Section 3.3).

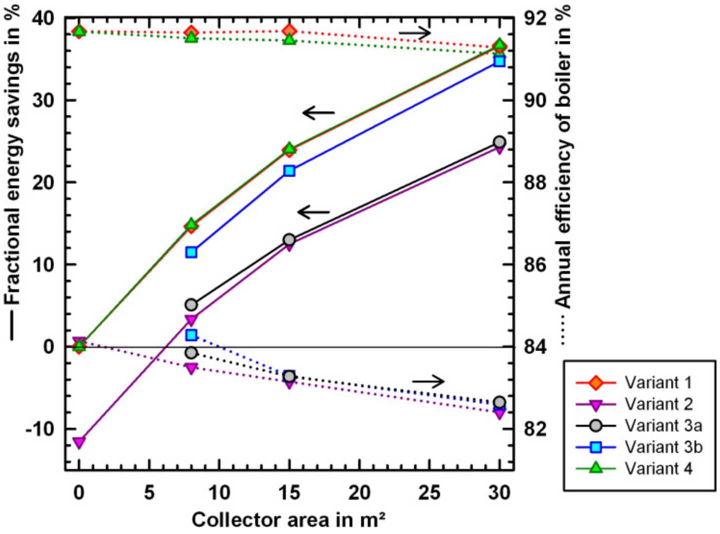

Fig. 3. Fractional energy savings and annual boiler efficiencies of all variants, variant 1 with solar buffer, variant 2 with solar and boiler buffer, variant 3a with combined solar and boiler buffer and hot water storage, variant 3b with combined buffer, external heat exchanger for DHW preparation and stratified charging and discharging devices, variant 4 with parallel connection of solar buffer and boiler (boiler set temperatur in simultaneous operation: 63°C).

In summary, the following conclusions can be taken from the study:

- The effects of a solar thermal system on the annual boiler efficiency are small.
- During simultaneous operation of solar subsystem and boiler, the solar preheated fluid increases the inlet temperature and thus the boiler efficiency decreases. If the portion of simultaneous operation is low (like in variant 1) the effect on the annual boiler efficiency is small. Furthermore, the solar collectors reduce the operation time of the boiler for hot water preparation with higher inlet temperatures. Thus, the overall impact by the solar thermal system on the annual boiler efficiency may be even positive.
- The number of boiler cycles affects the boiler efficiency at high temperature levels within the boiler. In this case, the ambient heat losses increase significantly, if the average boiler operation time decreases. The number of boiler cycles is reduced by the solar system and by a modulation burner, both leading to increasing average operation times.
- The boiler buffer of variant 2 reduces the boiler cycle rate but leads to additional heat losses and a higher boiler inlet temperature. The latter may be mitigated if the buffer storage is only used for space heating (not simulated).
- The combination of the solar and the boiler buffer in one bivalent buffer tank (variant 3a) decreases the storage heat losses and thus increases the energy savings if compared to variant 2. The storage heat losses are reduced even more, if the hot water preparation is performed via an external heat exchanger instead of the hot water storage tank. This system (variant 3b, equipped with charging and discharging devices) has lower storage heat losses and reaches almost the same fractional energy savings like variant 1. However, its hydraulic scheme is more complex.
- All variants with a boiler buffer unit (variant 2 and 3) have significant lower boiler efficiencies than variant 1 due to a higher boiler inlet temperature. Furthermore, the effects of the solar thermal system on the boiler efficiency are more pronounced. Since solar heat leads to higher temperatures in the

boiler buffer, the average annual boiler inlet temperature is increased if compared to variants 1 and 4. Thus, the lowest boiler efficiency occurs in variants 2 and 3 with a collector area of 30 m².

- The system layout of variant 4 does not lead to higher energy savings if compared to variant 1, which can be explained by the low portion of simultaneous operation of boiler and solar thermal system in variant 1. Under these circumstances the additional expense for the four-way valve and the more complicated system control is not worthwhile.
- The final energy savings are the most important indicator of solar thermal combi systems. The collector yield and the boiler efficiency are not sufficient for a full evaluation. Variant 3b with the lowest boiler efficiency has almost the same energy savings than variant 1 with the highest boiler efficiency.

From the simulation study presented in this paper, it may finally be concluded, that

- the solar heat does not show a negative influence on the boiler efficiency,
- the solar subsystem reduces the number of boiler cycles and enlarges its average operation time,
- each additional storage tank heated by conventional energy leads to lower final energy savings and
- simple system schemes like that of variant 1 do not have to lead to lower energy savings (in this study variant 1 has even the best performance).

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