Energetic Comparison of Different Instantaneous Water Heater Concepts in a Solar Combi-System for a Multi-Family House with TRNSYS

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Abstract

In order to avoid heating the entire storage to 60 °C to fulfill the hygienic regulations, the use of central instantaneous water heaters (IWH) in multi-family houses is advisable. The cold preheating zone enables temperature-sensitive regenerative heat generators to provide part of the required energy at a lower temperature level as part of a bivalent system. In this work, the influence of the circulation loss of the building and the technical properties of the IWH on the CO_2 emissions, the solar utilization ratio and the solar fraction of a bivalent system with solar thermal and gas boiler is investigated. For this purpose, the heat transfer capability of the IWH and, if available, the actuating time of the return flow diversion are varied in a broad range. These parameters are based on a market analysis and own laboratory tests. With constant tapping profile and constant collector area, the circulation load has the largest impact on CO_2 savings, but technical characteristics also significantly affect CO_2 savings (+/-12 %). This is due to the fact that a high heat exchange rate lowers both the required maximum storage temperature (-10 K) and the resulting return temperature. With a short actuating time of the return flow diversion, low return temperatures lead to low temperatures in the lower storage, which can be efficiently heated by the solar thermal system. For a multi-family house with 1 kW circulation losses, CO_2 savings of (36 - 48 %) can thus be achieved, depending on the IWH.

Keywords: instantaneous water heater, solar combi system, solar thermal, UA-value, return diverter, TRNSYS simulation, efficiency

1. Introduction

The final energy consumption (FEC) in Germany has remained almost unchanged over the last 10 years at 9000 PJ/a, which corresponds to a per capita consumption of about 30 MWh/a.

The heating sector accounts for just over half of the final energy consumption, with space heating and potable hot water consumption in the residential sector accounting for almost one-third of final energy consumption. The share of potable water heating is constant at around 5% of the FEC, while energy consumption for space heating is declining due to renovation measures and milder temperatures as a result of climate change (AGEB e.V., 2019). Of the approximately 36 million metric tons of CO_2 generated by domestic water heating, the residential sector accounts for the lion's share (3.9 % of the FEC) (cf. Fig. 1). In 2018, around 60% of the residential sector in Germany was made up of multi-family houses, which therefore account for a large proportion of these emissions (Statistisches Bundesamt, 2019)) .

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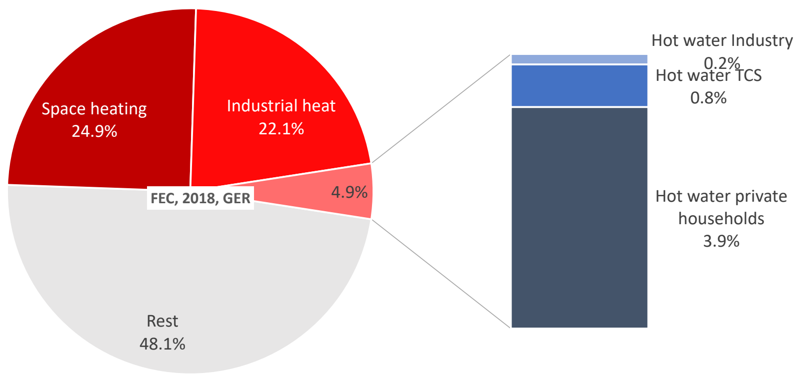

Fig. 1: Distribution of the German final energy consumption 2018 for different sectors and analysis of the domestic hot water sector (data from (AGEB e.V., 2019))

Modernization and renovation of the building stock not only reduces the energy required for space heating, but also the correspondent supply temperature level. The focus of science has been therefore shifted to the heating of potable water, as this is responsible for the maximum required temperature. Especially in large systems, hygienic operation rules are an obstacle for temperature-sensitive heat generators such as heat pumps and solar thermal (Pärisch et al., 2020b), but also for district heating based on renewable energies. Central instantaneous water heaters offer hygienic advantages due to less stagnant water (Rühling et al., 2018). The use of a buffer storage also leads to energy benefits, since the creation of a cold preheating zone can increase the efficiency of temperature-sensitive heat generators (Pärisch et al., 2020a). In order to benefit from these advantages, this paper investigates the technical properties of IWH through a parameter study with the simulation program TRNSYS to determine their influence on the efficiency of a solar combi system in a typical multi-family house. The work in this paper continues the previous investigation by Pärisch et al., (2020b) and extends it with a broader variety of parameters.

2. Solar thermal combi systems with instantaneous water heater

Solar thermal combi systems consist of solar thermal collectors and an auxiliary heating system, usually a gas boiler, but systems with an electric heater or heat pump are also conceivable. There are two possibilities for the supply of domestic hot water (DHW) by a solar thermal combi system (VDI, 2014). On the one hand, the DHW can be stored directly in a storage, on the other hand the (solar) energy is temporarily stored in a smaller buffer storage and the DHW is heated as required/on demand. Particularly in large-scale systems, the first option would require a very large quantity of DHW to be stored and heated completely to 60°C once a day to fulfill the hygienic requirements (DVGW e.V., 2004). In order to keep the stored amount of DHW as small as possible, a buffer storage is therefore used wherever possible (Zaß, 2012).

Not only the quality of the thermal storage (stratification efficiency and thermal insulation) has an influence on the efficiency of the solar thermal combi system, but also the IWH used. This has been studied in the past, especially with respect to small systems without circulation, which are often found in single-family houses (Poppi et al., 2016; Poppi and Bales, 2014; Ruesch and Frank, 2011).

Thus, the selection of the IWH has an impact on the cooling of the primary return and therefore the efficiency of the entire system. The size of the heat exchanger determines the minimum storage temperature needed to cover the required maximum load peak, which in turn depends on the tap profile used. Another aspect that affects the efficiency of the combi system is the hydraulic concept and the control strategy used. They should guarantee a constant DHW temperature on the one hand, but on the other hand they also have an influence on the return temperature. When comparing different hydraulic concepts and control strategies, a speed-controlled regulation of the primary pump by means of a microprocessor without a primary mixing valve turned out to be the most effective variant, since a very precise adjustment of the volume flow and an effective cooling of the return flow can be achieved here. But also proportional controller with regulating valve or turbine pump leads to energy savings compared to typical systems provided with internal heat exchanger. (Bales and Persson, 2003)

Differences between idealized heat exchangers (infinite transfer area) and real IWH with large heat exchangers and well-functioning control are minimal (Ruesch and Frank, 2011). The size of the heat exchanger has a significant impact on the electricity consumption in a solar thermal heat pump combi system, as it determines the required storage temperature (Poppi et al., 2016).

Maintaining storage stratification is one of the challenges posed by the use of DHW circulation. Thus, increased return temperatures have a negative impact on the efficiency of the system and, depending on the hydraulic and controller concept, can result in over 10 % higher energy consumption (Ruesch and Frank, 2011). In pure circulation operation, very high primary return temperatures occur, which explains the advantage of a temperature-dependent stratification of the primary return into the buffer storage, especially in the case of high DHW set point temperatures and the associated high temperatures in the circulation return (Peuser et al., 2009; Zaß, 2012). Since circulation is mandatory, especially for large potable water installations, such as in multi-family houses (DIN, 2012), the following section examines which technical characteristics of an IWH enable the most efficient solar thermal combi system for a large DHW installation.

3. Simulation boundary conditions

The investigations in this study are carried out in TRNSYS (version 17.02.0005) for a multi-family building with 8 apartments as described by Mercker and Arnold (2017). The DHW is provided by a central IWH, and a circulation system ensures comfort and hygiene. The central heating system consists, as shown in Fig. 2, of a solar thermal system and a gas boiler, which heat a buffer storage in bivalent mode. The reference system consists of a smaller buffer storage heated by a gas boiler.

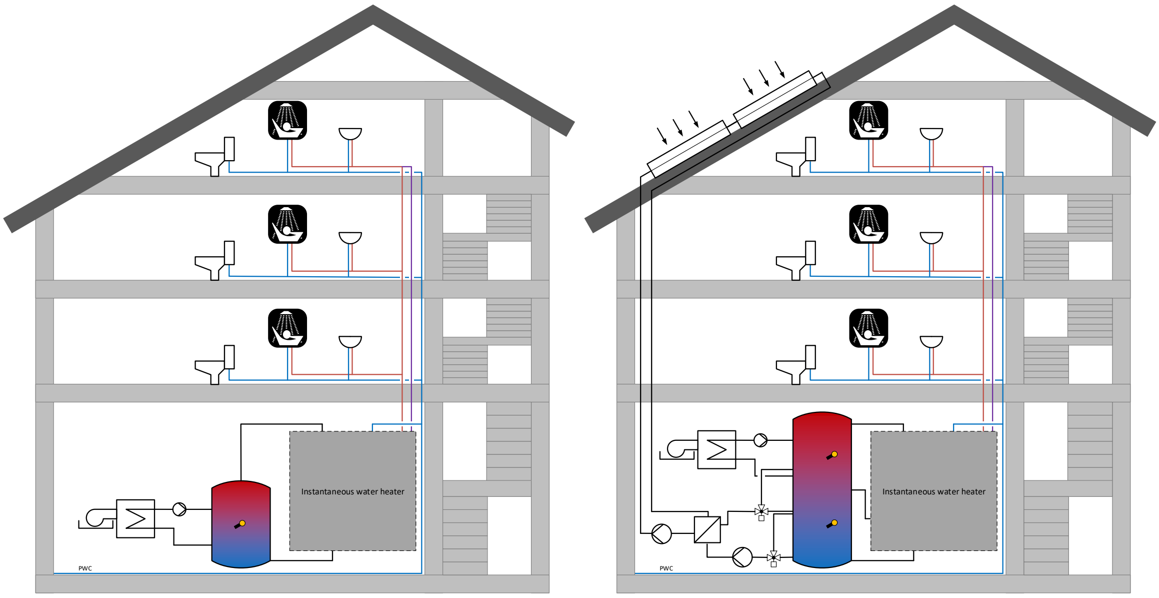

Fig. 2: Schematic of the investigated DHW-system of a multi-family house (reference system on the left side)

The tapping profile with a resolution of 1 min was generated for the building with 8 apartments using DHWcalc version 2.02b (Jordan et al., 2019). For 12 to 16 persons, a daily draw-off volume of 440 l at 60/10 °C is assumed, and summer vacations are also taken into account. An IWH is used, which can provide the required peak power of approx. 120 kW (≙34 l/min at 60/10 °C).

The minimum tapping time, which can be set in DHWcalc, is 1 min. The simulation time step is set to 2 s. However, 1 min is longer than the most tapping processes during hand washing, which is why we assume that the number of these events is underestimated. However, the heat demand occurs mainly during showering and bathing. For our results, we therefore expect to slightly underestimate the importance of return diversion.

The condensing gas boiler is controlled by a thermostatic control. The temperature sensor used for this purpose is located centrally between the supply and return pipes in the storage. There is a fixed difference of 5 K between the switch-on and switch-off temperature. The specific temperature values are part of a minimizing algorithm, which takes into account DHW penalties (see below).

The modulating condensing gas boiler is simulated with Type 204, which was developed at ISFH (Glembin et al., 2013). The boiler has a water content of 7.3 l and a heat output of 28 kW at 60 °C inlet temperature, which can be controlled with a minimum degree of modulation of 28 %.

Type 832 is used for the simulation of the solar thermal collector. The collector area is assumed to be 4 m² per apartment, which results in a total area of 32 m². This corresponds to the recommendations of Mercker and Arnold (

2017). The heat is transferred to the storage via an external heat exchanger with a *UA*-value of 120 W/K per m² of collector area (VDI, 2014). The temperature sensor for the control of the solar circuit is located in the middle between the flow and return of the lower solar circuit. In general, the solar flow can load the upper or lower part of the storage. This loading is temperature dependent. For the upper part to be loaded, the secondary outlet temperature at the heat exchanger must exceed the storage temperature of the upper solar circuit (measured in the middle between the flow and return of the corresponding circuit). The primary pump is started when the collector temperature exceeds the storage temperature by 15 K and is stopped when the difference is less than 5 K. The controller starts the secondary pump when the temperature in the primary side heat exchanger flow exceeds the storage temperature by 7 K and both pumps are stopped when this difference falls below 3 K. The pumps are operated in low-flow regime at 20 l/(m² h). At a storage temperature of 95 °C, the secondary pump is switched off and the primary pump runs until a collector temperature of 130 °C is reached. There is no communication between the heat generators, i.e. they are operated in bivalent-parallel mode.

For the simulation of the buffer storage Type 340 (Drück, 2006) is used. Two variants are simulated here: the first variant for the solar combi system has a volume of 1,600 l and a height of 1.8 m. For the reference system, the storage size was set to 640 l with a height of 0.72 m. The connection heights for both variants can be taken from Tab. 1 relative to the overall height of the storage. The heat losses of the storage are approx. 10 kWh/d.

Tab. 1: Parameters and relative connection heights of the storage

	Solar combi system	**Reference system**
Storage height	1.8 m	0.72 m
Storage Volume	1,600 l	640 l
Boiler flow pipe	0.8	0.5
Boiler return pipe	0.6	0.01
Upper solar flow pipe	0.65	-
Lower solar flow pipe	0.45	-
Upper solar flow return	0.45	-
Lower solar flow return	0.05	-
IWH flow pipe	1	1
IWH return pipe	0.01	0.01
IWH circulation mode return pipe	0.5	0.1

As reference we assume thermostatic mixing valves for the taps in the apartments with a set temperature of 45 °C, since this temperature corresponds to the DHWcalc profiles. The volume flow is recalculated based on the DHWcalc file and a fluctuating cold water temperature as described by IEA TASK 32 (Heimrath and Haller, 2007). The flow rate through the IWH $\dot{V}_{IWH}$ is given by

$$\dot{V}_{IWH} = \dot{V}_{tap} \cdot \frac{\vartheta_{tap,45°C} - \vartheta_{PWC}}{\vartheta_{pipe,out} - \vartheta_{PWC}} \qquad \text{(eq. 1)}$$

where $\vartheta_{pipe,out}$ corresponds to the variable hot water temperature before the mixing valve.

To find the lowest possible set temperature for the gas boiler, penalties are introduced. The simulation is aborted and not investigated further when the hot water temperature $\vartheta_{pipe,out}$ drops below 44 °C or the temperature at the outlet of the IWH drops below 60 °C. ‘

For circulation, 3 variants are considered. The basic variant assumes an existing building with 48 m uninsulated pipes. This corresponds to a 4-floor building with 3 m of pipe duct length in each floor for flow and return. In this case, the circulation volume flow is 160 l/h, whereby the return temperature does not fall below 55 °C in steady-state operation. This corresponds to losses of approx. 1070 W. In order to investigate the influence of the circulation, 2 further simplified variants were investigated: one with losses of approx. 200 W (representing insulated pipes) and one with losses of approx. 5350 W (representing longer pipes and more junctions). For simplification purpose, the pipe length and the volume flow were multiplied by the factor 0.2 and 5, respectively. This results in circulation volume flows of 32 l/h and 800 l/h. During a tapping event, the circulation volume flow is set to 0 l/h for simplicity.

4. Investigated parameters

Many technical properties of IWH are not accessible to the specialist planner and installer. This makes it difficult for them to choose the correct product for regenerative heat supply systems, especially with regard to efficiency and sustainability, but also with regard to economic efficiency.

In order to address this problem, four module types of electrical IWHs are considered, which were identified during a market investigation. The hydraulic circuits of these module types are schematically shown in Tab. 2.

Tab. 2: Schematics for the investigated IWH

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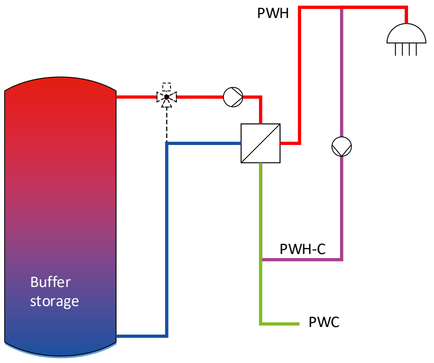
I Standard

Electronically controlled instantaneous water heaters normally use a modulating circulating pump. Some manufacturers use a 3-way valve to modulate the thermal power. These products with small *UA* -values are typically installed in small systems without circulation.



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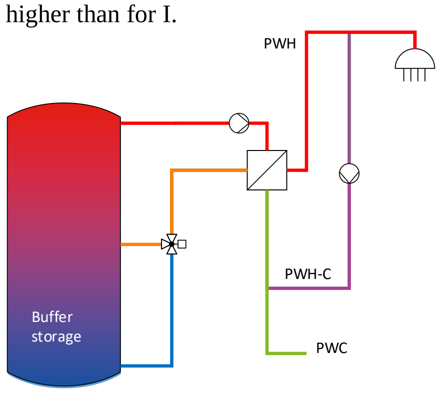
II Standard with return flow diverter

With circulation, a return flow diverter is often used to improve the temperature stratification. Shown here is a 3-way switching valve with a specific actuating time. It is varied between 2 s and 130 s. An actuating time below 2 s can be achieved by using two pumps in the two return flows, for example. *UA* -values are higher than for I.



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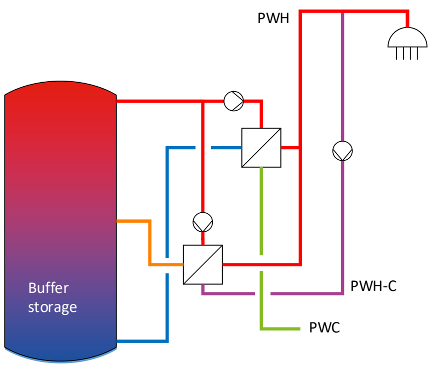
III Standard with circulation heat exchanger in parallel

Some products use a separate heat exchanger for circulation. With this parallel connection, the circulation heat exchanger and the associated pump can be optimised for the small volume flows. Actuating time is below 2 s and *UA*-values are slightly higher than for II.



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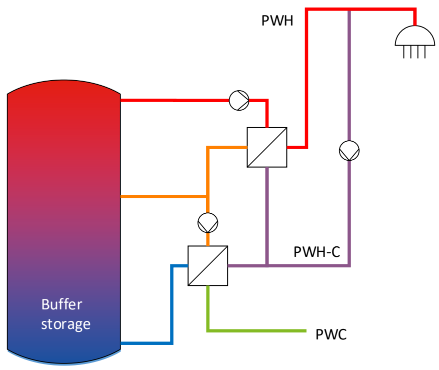
IV Standard with circulation heat exchanger in series

Alternatively, it is conceivable to connect two heat exchangers in series. This enables particularly good cooling during tapping operation and highest *UA*-values. Actuating time is also below 2 s.



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Basically, the IWH differ in the specific heat transfer rate, which is abbreviated as *UA* (note that it indicates here a property of the IWH and not only of the heat exchanger) and the actuating time between circulation and tapping mode. In Fig. 3 the three most important quality characteristics for the thermal energy efficiency are shown, which are influenced by these properties. Here, a module based on Concept II is used, which is used in TRNSYS to model all module types.

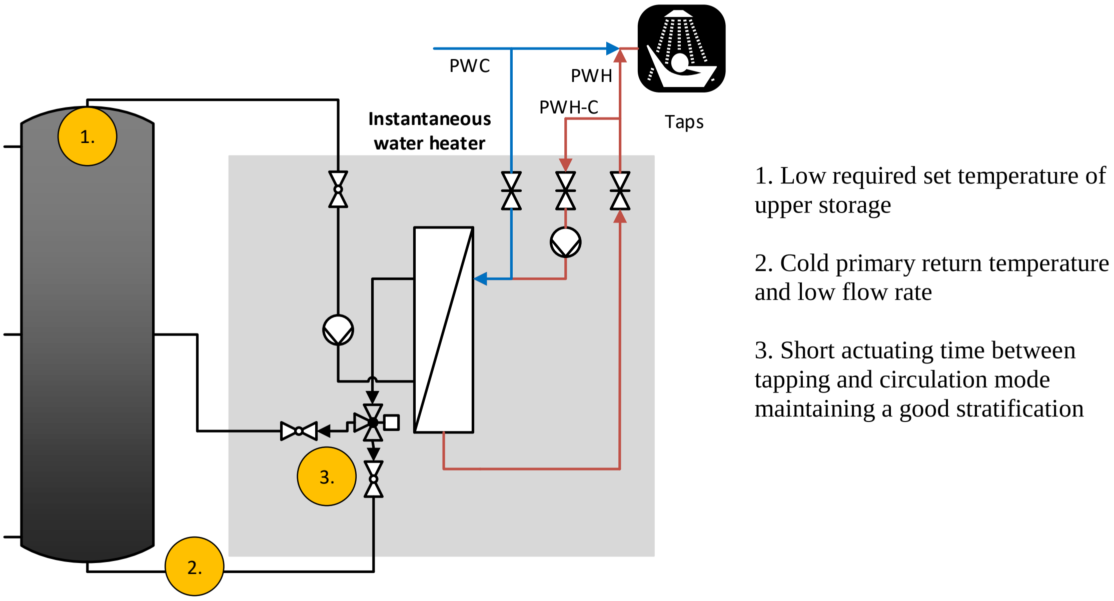

Fig. 3: Generic instantaneous water heater model for simulating large DHW-systems with three quality measures

To keep the thermal losses as low as possible and the solar fraction (or heat pump fraction) as high as possible, a low required set temperature (**point 1**) is required. This set temperature is determined by the temperature difference required by the module between the heating water inlet and the DHW outlet. The temperature difference depends not only on the heat exchanger but on the entire module hydraulics.

Another crucial point is the return temperature of the primary side (**point 2**). If this is lower, it increases the efficiency of all heat generators and leads to lower volume flows on the primary side and thus to less mixing in the storage.

In order to maintain the stratification of the storage, the return of the primary side is connected to the center of the storage in pure circulation mode. The circulation inlet has a temperature of at least 55 °C at the central IWH, so that this temperature is not undercut on the primary side. If tapping occurs, the return temperature drops sharply due to the dominant cold water temperature and the three-way reversing valve must switch to the lower storage connection with the shortest possible actuating time in order to maintain the storage stratification (**point 3**).

To determine the specific heat transfer rates (*UA*-values), we carried out laboratory measurements with several IWHs. We found that the *UA*-values can be approximated with the following equations.

$$UA = f_\vartheta \cdot \left(-3\frac{W/K}{(l/min)^2} \cdot \dot{V}_{sec}{}^2 + 295\frac{W/K}{l/min} \cdot \dot{V}_{sec}\right) \cdot f \qquad \text{(eq. 2)}$$

$$\text{with } f_\vartheta = \left(1.0395 - 0.008 \cdot (\vartheta_{P,in} - 60°C)\right) \qquad \text{(eq. 3)}$$

The definition of the temperature correction factor f_ϑ (see eq. 3) is limited to primary inlet temperatures $\vartheta_{P,in}$ between 60 and 90 °C. The specific heat transfer coefficient (*UA*) is obtained in W/K where the secondary side flow rate $\dot{V}_{sec}$ is in l/min. The performance of different IWH modules can be adjusted by the factor f, which was varied between 1.0 and 2.5 in these simulations.

The results of the *UA*-value calculation according to eq. 2 compared to six real measured stations are shown in Fig. 4 for primary inlet temperatures of 70 °C and 90 °C. The cold water temperature is 10°C and the domestic hot water temperature is 60°C. A standard system for small systems according to Concept 1 is mapped using a factor f = 1.0 to 1.5. The performance is sufficient for the multi-family house tapping profile shown, if the temperature in the buffer is high enough. Stations according to this concept are the products Ia, Ib and Ic. Larger modules for multi-family houses according to concept II and III are represented by f = 1.5 to 2.0. Particularly efficient heat exchangers or concept IV with 2 heat exchangers connected in series are represented by a factor f = 2.5. In general, the measured IWHs are only a random sampling. Each IWH module concept can achieve the same characteristics, but at different costs, which is why this study does not consider station concepts but only characteristics.

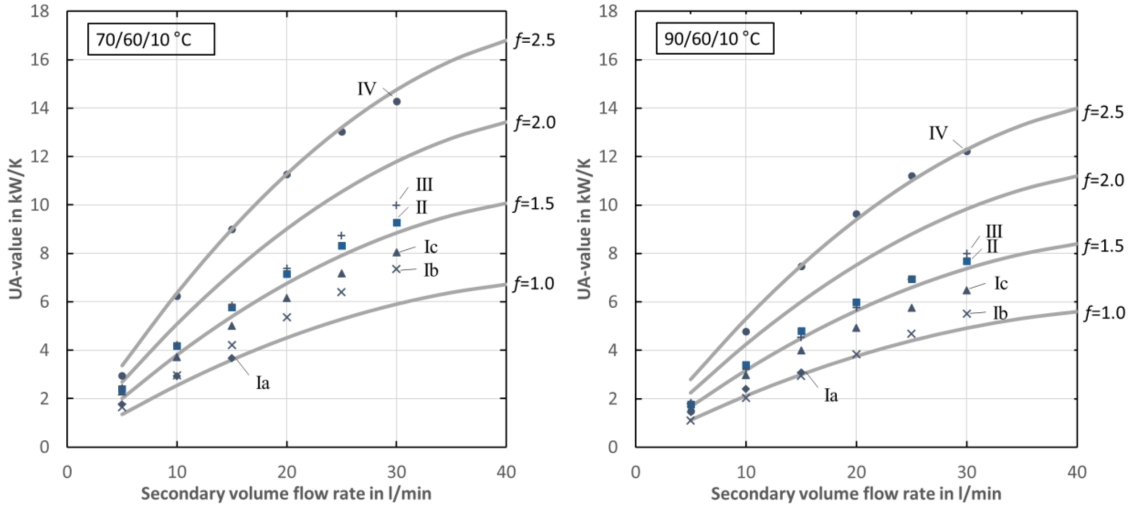

Fig. 4: Comparison of different measured *UA* -values (points) of six different IWH at 70 °C/60 °C/10 °C (left) or 90/60/10 °C (right) with calculation results according to eq.2 for different factors *f* (lines)

In circulation mode, a constant *UA* value is assumed. This depends on the volume flow rate and accounts to, 500 W/K at 0.2 kW and 1 kW circulation loss and to 2000 W/K at 5 kW circulation loss.

Type 84 (moving average) is used to model the actuating time (t_{RL}) of the primary return between the lower and middle storage areas. It is between 2 s and 130 s. Tab. 3 shows all values and an overview of all varied parameters. The upper set point temperature of the storage used for the control of the gas boiler is determined via minimization.

For the reference system the IWH concept I with a *UA*-value f = 1.0 is used, the return flow is always at the bottom inlet.

Tab. 3: Overview of the varied parameters in the simulation

Factor *f* for *UA*	**Actuating time t_{RL}**	**Circulation heat loss rate**	**Set temperature of upper storage**
1.0	2 s	1.07 kW	Find minimum ()
1.5	18 s	0.20 kW	
2.0	34 s	5.35 kW	
2.5	50 s		
	66 s		
	82 s		
	98 s		
	114 s		
	130 s		
	Always bottom		

5. Results

When evaluating the simulations, the mean upper storage temperature, which is typically higher than the set point, is considered first (Fig. 5). Here, a clear dependence on the *UA*-value is noticeable: as expected, the required storage temperature decreases with increasing *UA*-value. For the return diversion (effects represented by the error bar) and the circulation losses, on the contrary, no clear tendency can be observed. This can be probably explained by slight changes in the recharging behavior of the heat generators and thereof resulting penalties. Real DHW installations will be more tolerant with regard to short-time temperature drops of the outlet temperature than our penalty conditions, so that lower storage temperatures would be possible.

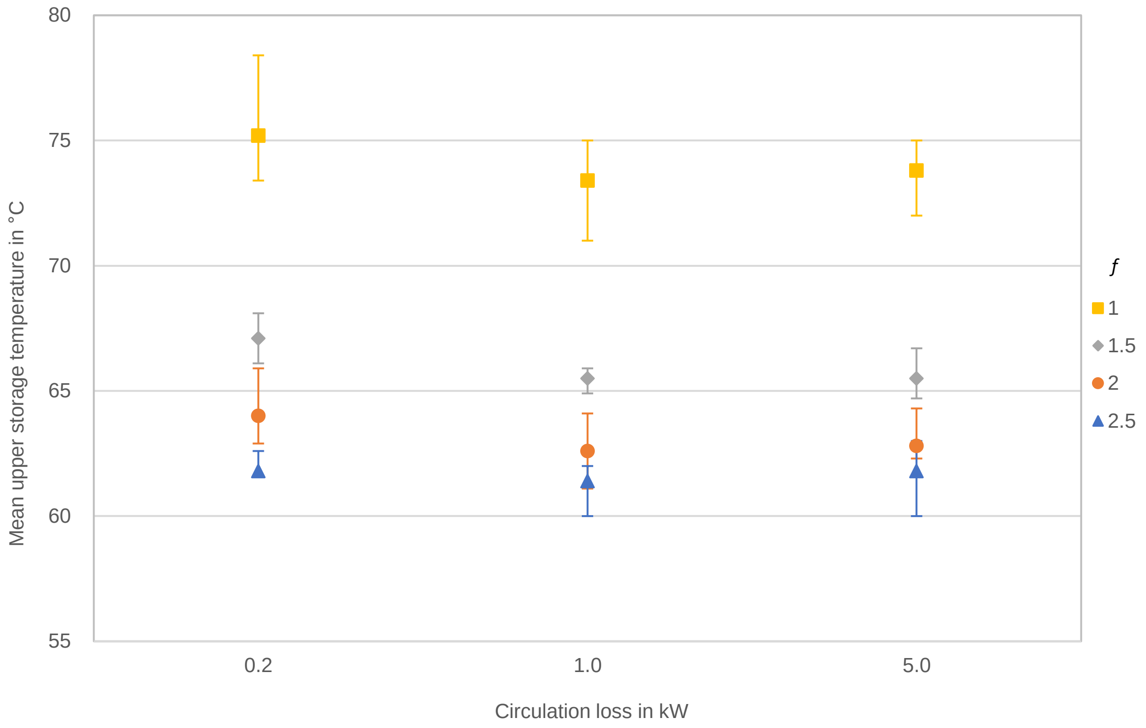

Fig. 5: Mean upper storage temperature depending on circulation loss an *UA*-value for the solar combi-system

The main focus of the evaluation, is on the CO_2 savings $f_{sav,CO2}$ (cf. eq. 4) compared to the respective reference system. There is one reference value for each circulation loss.

$$f_{sav,CO2} = 1 - \frac{(Q_{Gas} \cdot f_{Gas,CO2})}{(Q_{Gas} \cdot f_{Gas,CO2})_{ref}} \qquad \text{(eq. 4)}$$

For this, the gas consumption Q_{Gas} of the respective system is multiplied by the emission factor $f_{Gas,CO2}$=250 gCO_2-eq/kWh$_{Gas}$ for natural gas (Fritsche, 2016) .This also takes upstream emissions and other greenhouse gases into account. The electricity consumption of the system, for solar thermal and gas burner is negligible.

A comparison of the bivalent system with the reference system shows that the CO_2 savings clearly depend on the circulation load, as the collector area is constant (see Fig. 6).

A low circulation loss with the same tap profile leads to significantly higher CO_2 savings. Thus, in the case *UA*-value *f* = 1 and no return diversion the savings increase from 15% at 5 kW to 36% at 1 kW and 51% at 0.2 kW. With higher circulation losses, the total consumption of the system increases and this additional energy is required at a temperature level between 55 and 60 °C, which can be reached much less frequently compared to preheating the cold water at the storage tank inlet.

Both varied parameters of the IWH have an influence on the results. Fast switching of the return diversion has a positive effect on CO_2 savings, as it contributes to the formation of a cold zone in the lower part of the storage. Furthermore, a good heat transfer performance *f* of the IWH leads to lower required storage temperatures (see Fig. 5) which in turn ensures that less energy has to be provided by the gas boiler.

In general, all concepts manage to supply the multi-family house with hot water without penalty. With a circulation loss of approx. 1 kW, however, IWH for single-family houses can only achieve a saving of 36 %, and with an improvement of the *UA*-value, up to 5 pp. can be gained. The influence of the return diversion shows a large influence especially for higher *UA*-values, thus the introduction of a slow return diversion with a actuating time of 130 s already leads to an improvement up to 4 pp. and a fast return diversion to a further improvement by about 4 pp. The influence of the *UA*-value also increases to 9 pp.

A similar behavior can be observed for the other two investigated circulation losses, where the scatter caused both by the *UA*-value change and by the return diversion decreases for large circulation volume flows and increases for small ones, which can also be explained by the reasons already described.

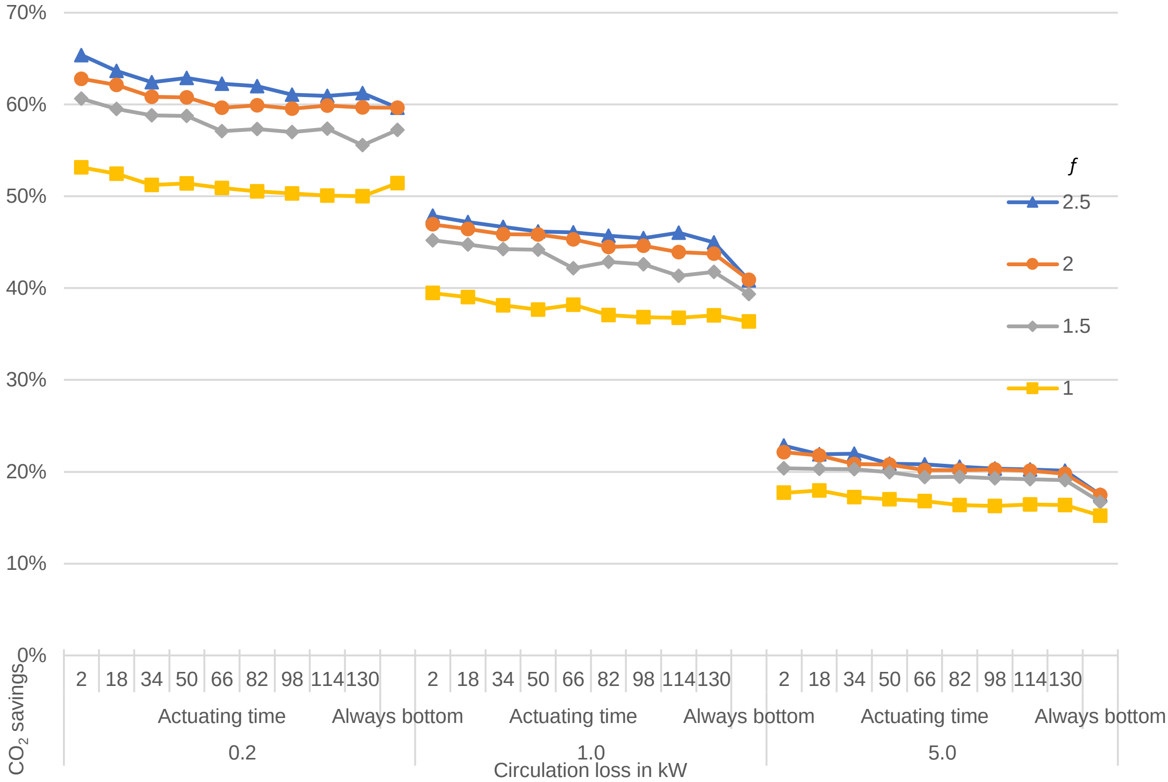

Fig. 6: Annual CO_2 savings of the system depending on *UA*-values, actuating times and circulation losses

Furthermore, we calculated the solar fraction f_{sol} according to eq. 5. This value gives information whether a good storage stratification occurs and a cold preheating zone is created. For this purpose, the solar energy Q_{sol} fed into the storage is put into relation with the sum of Q_{sol} and the energy of the gas boiler Q_{Boiler}.

$$f_{sol} = \frac{Q_{sol}}{Q_{Boiler}+Q_{sol}} \qquad \text{(eq. 5)}$$

The solar fraction shows an analogous behavior to the CO_2 savings. The solar utilization ratio η_n is calculated according to eq. 6.

$$\eta_n = \frac{Q_{sol}}{Q_G * A_{koll}} \qquad \text{(eq. 6)}$$

Here, the proportion of the solar radiation energy Q_G incident on the collector area A_{koll} used by the system is calculated.

Fig.7 shows the solar fraction and the solar utilization ratio over the specific energy demand per collector area. Different technical properties of IWH cause a variation of 12 % in both, solar fraction and solar utilization ratio. Here the daily specific energy demand per m² of collector area is used, which results from the energy demand for tapping and circulation load, whereby in this paper the circulation load is the only variable.

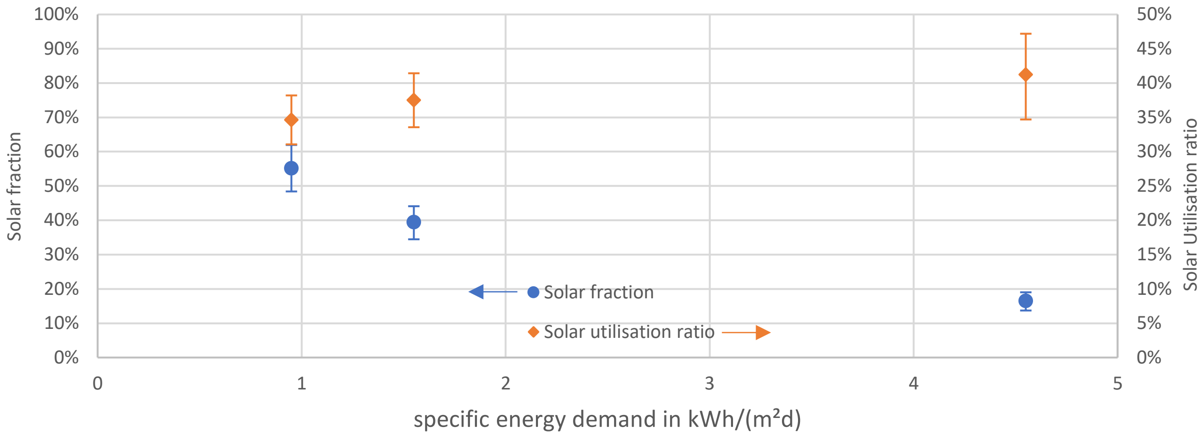

Fig. 7: Solar fraction and utilization ratio of the solar thermal system with different specific heat demands (error bars show the variation due to different IWH properties)

6. Summary

Over the last years, the heating energy demands of residential buildings have been reduced more and more. As a result, the focus has shifted to heating of domestic hot water, as it determines the required temperature level of the heat generation system. For large domestic hot water installations, IWH systems in combination with a bivalent heating system have emerged as a possible solution for decarbonization, as they create a cold preheating zone in the buffer storage which enables the efficient operation of renewable heat generators such as heat pumps and solar thermal systems.

We investigated an exemplary bivalent heating system consisting of solar thermal and gas boiler for a multi-family house. In addition to different circulation losses, 4 concepts of IWHs with different parameters for the heat exchanger capacity and the return diversion were analyzed. The variation of circulation losses between 0.2 to 5 kW changes the solar fraction between 14 to 50 %, which argues for a consistent insulation of all pipes of the circulation circuit and a compact design of the installation. With regard to the results of the low circulation losses, an effective IWH with high *UA*-values and short actuating times of the return diversion can increase the CO_2 savings from 50 % to 65 %. However, the sensitivity of CO_2 savings with regard to these parameters decrease with low solar fraction (high circulation losses).

For the given demand profile and optimization rule, the required storage temperatures (between 72 and 84 °C), which play a major role for solar thermal systems but also for heat pump systems and the reduction of district heating temperatures, are mainly dominated by the *UA*-value. The actuating time of the return diversion has no significant influence on the required storage temperatures.

In general, the simulation results show that a return diversion is advantageous and if it is present, that it should be as fast as possible. This can increase the efficiency of the solar thermal system.

7. Outlook

The results are influenced by the penalty rule that needs further investigation. How long can the outlet water temperature of the water heater be lower than 60 °C without being a design error? This is especially relevant for temperature sensitive heat generators, such as heat pumps, which should be investigated in future work. Furthermore, the influence of other tapping profiles and a variable collector area should be investigated.

8. Acknowledgement

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