# Parameter study of four different instantaneous water heaters in a solar assisted multi-family-house with TRNSYS

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**Abstract**

The use of instantaneous water heaters avoids heating of the complete storage to 60 °C, which is necessary to fulfill hygienic requirements. This allows temperature sensitive renewable heat supply systems, like solar thermal or heat pumps, to decarbonize the heat demand in bivalent systems. Technical properties of the instantaneous water heater (IWH), like the specific heat transfer rate *UA* and switching time of the return flow diverter, have been derived from a market survey and lab tests. A suitable setting/choice of these properties can increase the solar thermal yield, improve the temperature stratification and may reduce the maximum required temperature in the upper part of the storage. This allows a solar thermal collector to substitute more fossil fuels and to reduce more effectively $CO_2$-emissions. A parametric study with a DHW supply system of a multi-family house with 8 apartments reveals that the $CO_2$-savings by solar thermal heat are highly sensitive to these technical properties. They range from (35 % up to 46 %).

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

## 1. Introduction

In Germany, the final energy consumption per capita is about 30 MWh/a, equivalent to a total amount of 9000 PJ/a, and almost unchanged in the last 10 years (cf. Fig. 1).

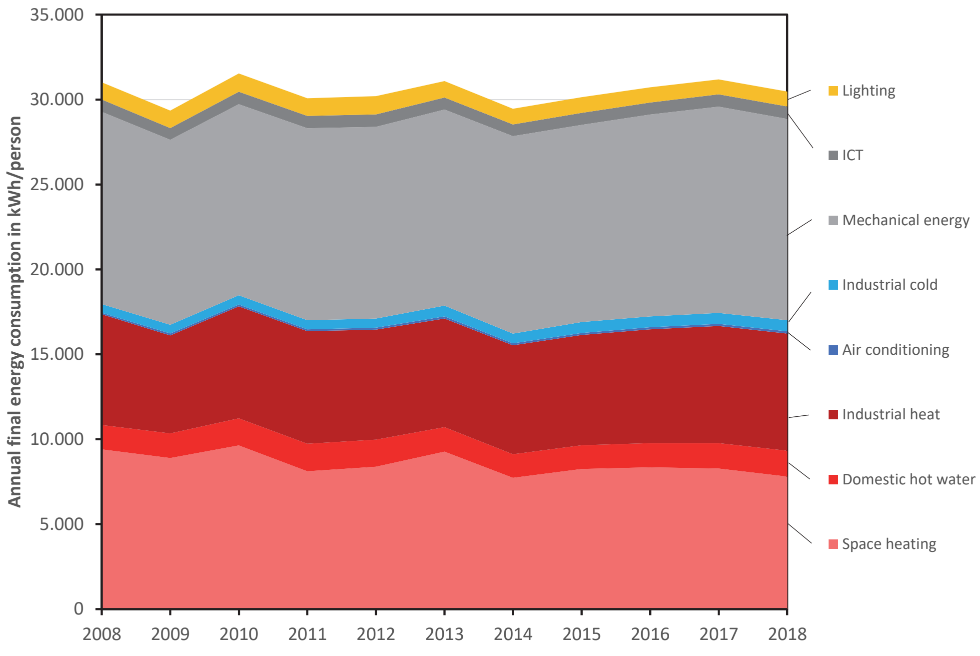


**Fig. 1: German final energy consumption of the years 2008-2018 for different application sectors (data from AGEB e.V. (2019))**


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Slightly more than half of the final energy consumption (FEC) is accounted for by the heating sector as a whole and almost a third of the FEC is related to space heating and potable hot water in the residential sector. The consumption of space heating is slowly declining due to renovation activities and climate change. Roughly 5 % of the FEC is accounted for by the heating of drinking water, which after all generates around 36 mil. tons of $CO_2$. The residential sector accounts for the largest share, 3.9 % (cf. Fig. 2). According to surveys conducted by the statistical offices of the federal and state governments, the residential sector in 2018 consists of around 60 % multi-family houses and 40 % single-family houses (Statistisches Bundesamt, 2019).

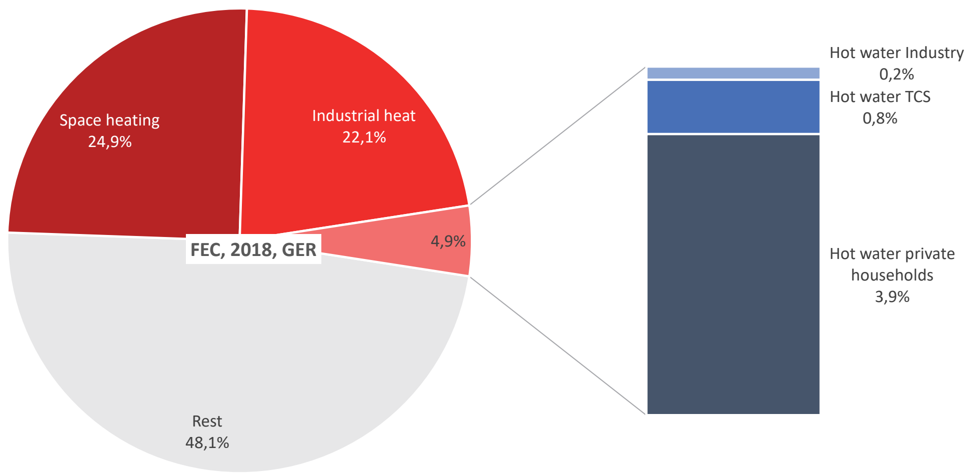



**Fig. 2: Distribution of the German final energy consumption 2018 for different sectors and analysis of the domestic hot water sector (data from AGEB e.V. (2019))**

The modernization and renewal of the building stock is not only accompanied by a declining share of energy for space heating, but also by a reduction in the temperatures required for heating. The heating of domestic hot water is coming into focus, not least because it determines the necessary temperature level of the heat generator. As a result, the heating of drinking water - especially in large-scale facilities - is an obstacle for temperature-sensitive heat pumps, solar thermal energy and heating networks based on renewable energies.

This paper presents the German Standards for the operation of domestic hot water heaters (DHW heaters) resulting from drinking water hygiene. Central instantaneous water heaters (short: IWH) are regarded as one solution for dissolving or reducing the obstacles. Due to the lack of product and test standards, a comparability of IWH with regard to important technical properties is not given. On the basis of a parameter study in TRNSYS the influence of these technical properties on the energy efficiency of a typical apartment building is investigated.

## 2. Hygienic regulations

Drinking water is not sterile, but contains (in low concentration) naturally occurring bacteria, including the genus Legionella. Based on projections, Legionella bacteria cause about 15,000 - 30,000 pneumonia cases in Germany every year (von Baum et al., 2008), of which about 15 % are fatal. They can multiply to a critical number in domestic hot water installations if the generally accepted codes of practice are disregarded, and can enter the lungs in droplets. The purpose of the regulations is to prevent this (TrinkwV, 2018) and there are a number of standards and guidelines that specify the generally accepted codes of practice (DVGW W551, 2004; DIN EN 806-2, 2005; DIN 1988-200, 2012; VDI/DVGW 6023, 2013). An essential parameter for the reproduction of the legionella is the water temperature (Brundrett, 1992), but also (stagnation) time, nutrient supply and turbulence in the pipe have an influence (Kistemann and Bausch, 2019).

The normative requirements for the hygienic operation of drinking water heaters currently differentiate between large and small systems or central and decentral systems (see Table 1).

According to DVGW worksheet W551 (DVGW W551, 2004) and DVGW-information no. 90 (DVGW, 2017), small systems are systems in detached and semi-detached houses as well as drinking water installations in which the content of the DHW storage is less than 400 l and the respective pipe volume to each tapping point is less than 3 l. Reducing the outlet temperature of the domestic water heater (abbreviation: PWH = potable water hot) below 60 °C is only permissible in small systems. In this case, a minimum of 50 °C is recommended. A circulation line is required from a pipeline volume of 3 l to the most distant tapping point. Its return temperature (PWH-C) must not drop below 55 °C.

(DIN 1988-200, 2012) distinguishes between central and decentral water heaters and introduces water exchange as the criterion for a tolerated temperature reduction at the outlet of central domestic water heaters. If the entire content of the domestic hot water installation is replaced within three days, the temperature may be reduced by up to 10 K. This could be achieved, for example, with looped-through ring installations with automatic rinsing systems. For decentral water heater, which correspond to small systems, the PWH temperature may be 50 °C or even below dependent on the pipe content.

The temperature of the domestic cold water (abbreviation PWC = potable water cold) may not exceed 25 °C (VDI/DVGW 6023, 2013).

**Table 1: Overview of the two German Standards regarding the operation of drink water installations**

| | **DVGW W551:2004** | | **DIN 1988-200:2012** | |
|---|---|---|---|---|
| | **Small system** | **Large system** | **Central WH** | **Decentral WH** |
| **Outlet temperature of water heater (PWH-temperature)** | - Recommendation: ≥ 50 °C[1] | 60 °C | ≥ 60 °C (≥ 50 °C, if water exchange within 3 days) | ≥ 50 °C (< 50 °C, if pipe content ≤ 3 l) |
| **Preheating stages of bivalent storage water heater** | 1 x per day 60 °C, if storage volume ≥ 400 l | 1 x per day 60 °C | | |
| **Circulation** | Mandatory, if pipe content > 3 l | Mandatory | Mandatory, if pipe content >3 l | - (unless pipe content >3 l) |

[1] with mandatory possibility to heat up to 60 °C

Central instantaneous water heaters enable domestic hot water (DHW) installations with low volumes of hot drinking water. The frequent water exchange shifts the hygienic problem of bacterial proliferation to the biofilm inside the pipes, drinking cold water and stagnant water in pipes. A so far only hypothetical reduction of the hot drinking water temperature would have the following beneficial effects on these hygiene parameters:

- reduced risk of warming potable cold water due to less heat losses
- increased flow velocity in the hot drinking water pipe due to different mixing ratio at the tap
- more frequent exchange of hot drinking water

The beneficial effect of a reduced operating temperature on the energy consumption of generation, storage and piping system is obvious. Nevertheless, the set temperature from the IWH is 60 °C in this parametric study.

Independently of a hypothetic temperature reduction, IWH with buffer storage catalyze the decarbonization of large DHW installations combined with solar thermal energy (or heat pumps). The colder preheating stage of the buffer storage leads to a higher efficiency of these temperature-sensitive heat generators.

Decisive for the economic efficiency and acceptance of such a modernization are high-quality IWH and good planning. Unfortunately, the market is characterized on the supplier side by a lack of transparency regarding the relevant technical features of the instantaneous water heaters and on the planner side by ignorance regarding loads and dimensioning. Ruesch and Frank (2011) and Lampe and Bölter (2017) have started a standardization process for IWH without circulation and this paper aims at contributing to the definition of efficiency properties of IWHs for large DHW installations.

## 3. Simulation boundary conditions

Fig. 3 illustrates the investigated heat supply system using the example of an apartment building, (Mercker and Arnold, 2017) with 8 apartments and a heated living area of 520 m², which was mapped in TRNSYS 17. A central IWH supplies the taps and the circulation with heat from a buffer storage tank heated bivalent by a solar thermal system and a gas boiler.

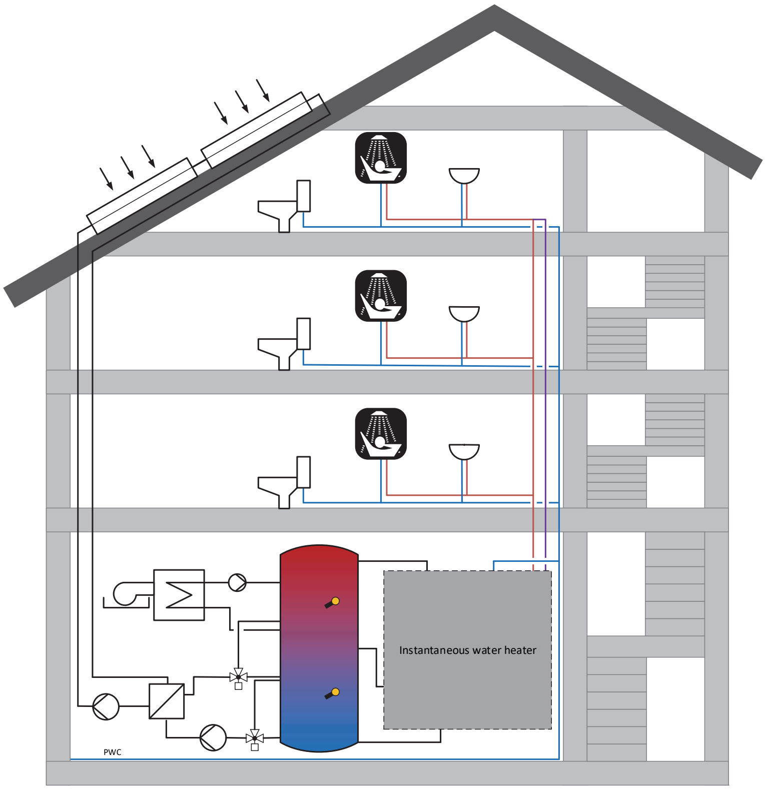



**Fig. 3: Schematic of the investigated DHW-system of a multi-family house**

The condensing gas boiler is controlled by a normal thermostatic control with a temperature sensor in the storage, whereby the temperature sensor is located centrally between the supply and return pipe. For the gas boiler, the switch-on temperature is 65 °C and the switch-off temperature 70 °C. Both parameters, coupled together with a fix 5 K difference, are part of a minimization algorithm, which also accounts for DHW penalties (see below).

The solar thermal system is simulated with Type 832 with a constant collector area of 32 m², which corresponds to 4 m² per apartment as recommended by Mercker and Arnold (2017). The external plate heat exchanger comprises an UA-value of 120 W/K per m² collector area according to VDI 6002-1 (2014). The controller activates the primary pump if the difference between collector temperature and storage temperature (midway between flow and return of lower solar section) exceeds 15 K and stops it if it falls below 5 K. The secondary pump starts if the heat exchanger inlet temperature on the primary side exceeds the storage temperature by 7 K. Both pumps stop if the temperature difference of primary heat exchanger inlet and storage drops below 3 K. On the primary and secondary side, the capacity flows are adapted to each other. The operating mode of the pumps is low-flow with 20 l/(m²·h). The maximum storage tank temperature is 95 °C, from which only the secondary pump is switched-off. The primary pump is switched-off if a collector temperature above 130 °C occurs to account for the evaporation temperature. The solar flow can either load the upper or lower storage tank section depending on the temperatures. To load the upper solar section the secondary outlet temperature has to exceed this section temperature (midway between flow and return).The two heat generators are operated in bivalent-parallel mode, i.e. there is no communication, for example to suppress auxiliary heating.

The gas boiler is simulated with the Type 204 developed at ISFH from Glembin et al. (2013). The modulating condensing gas boiler has a heat output of 28.5 kW at 60 °C inlet temperature. Other important parameters are: minimum degree of modulation 28 %, water content 7.3 l.

The buffer tank with a volume of 1600 l is simulated with Type 340 (Drück, 2006). It has a height of 1.8 m and the relative connection heights for boiler flow pipe are 80 %, for boiler return pipe 60 %, for solar flow pipe 45 % (lower) and 65 % (upper), for solar return pipe 5 %(lower) and 45 % (upper), for IWH flow pipe 100 %, for IWH return pipe 0 %, for IWH return pipe in circulation mode 50 %. The storage tank losses amount to about 10 kWh/d.

DHWcalc version 2.02b was used for the definition of the tapping profile (resolution 1 min) of the assumed building with 8 apartments (Jordan et al., 2019). The daily draw-off volume of 440 l at 60/10 °C corresponds to 12-16 persons. The summer holidays are taken into account. See Pärisch et al. (2020) for a frequency distribution of the tap load profile and a comparison to measured values. The peak output approximately 80 kW (≙23 l/min at 60/10 °C) allows using IWH for single and two-family houses also for this multi-family house.

We assume thermostatic mixing valves at the apartments with a set temperature of 45 °C and recalculate the tapping flow rate $\dot{V}_{tap}$ on the basis of the DHWcalc file. The flow rate through the instantaneous water heater $\dot{V}_{IWH}$ is modified for different temperatures leaving the pipe $\vartheta_{\text{pipe,out}}$.

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

If either the water temperature leaving the pipe $\vartheta_{\text{pipe,out}}$ drops below 44 °C or the water temperature leaving IWH drops below 60 °C for more than 0.15 h, the simulation is stopped. In this way the DHW penalties are minimized and the lowest set temperature for the gas boiler of upper storage is found.

The heat loss rate in circulation mode results from a pipe length of 48 m of uninsulated pipe (assumption for existing buildings) of around 1070 W. The volume flow rate of circulation is 160 l/h, so that the return flow temperature does not fall below 55 °C in steady-state operation. To simplify matters, we assume that the circulation volume flow is zero during tapping events.

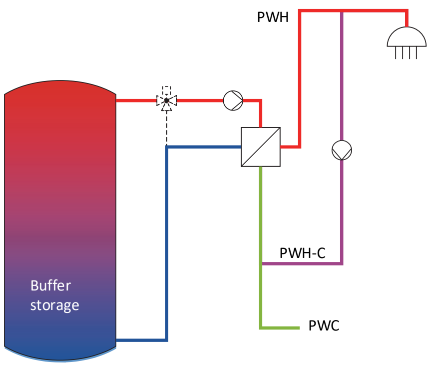
Simulation time step is 2 s. We adjusted the minimum draw-off duration in DHWcalc to 1 min (smallest possible value). As most tapping events for hand washing are less than 1 min in real buildings, we assume that DHWcalc underestimates the amount of small tapping events. On the other hand, most heat demand occurs for showering and bathing. Therefore, we estimate that our results will slightly underestimate the importance of return diversion.

## 4. Investigated parameters

Technical properties of the IWH, that are largely inaccessible to the specialist planner and installer and thus are not comparable, can influence the profitability of partially regenerative heat supply systems, their efficiency and the $CO_2$ savings achieved.

In the following investigation, TRNSYS 17 is used to simulate the essential technical features of IWHs and their energetic relevance for an exemplary large domestic hot water installation. Based on a market survey of electronic IWHs, four types of modules are identified. These hydraulic variants of the IWH are shown in simplified form in Table 2.

**Table 2: Schematics for the investigated IWH**

<table>
<tr>
<td>I Standard<br><br>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.<br>
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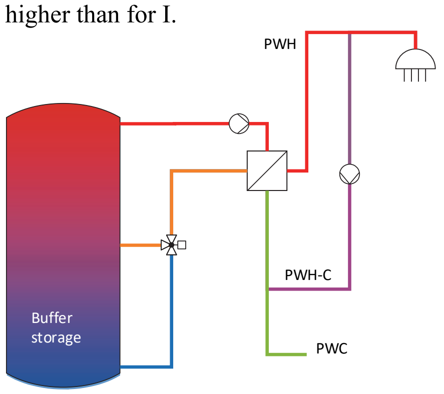
<td>II Standard with return flow diverter<br><br>With circulation, a return flow diverter is often used to improve the temperature stratification. Shown here is a 3-way switching valve with a specific actuating time. It is varied between 2 s and 50 s. A switching time below 2 s can be achieved by using two pumps in the two return flows, for example. UA-values are higher than for I.<br>
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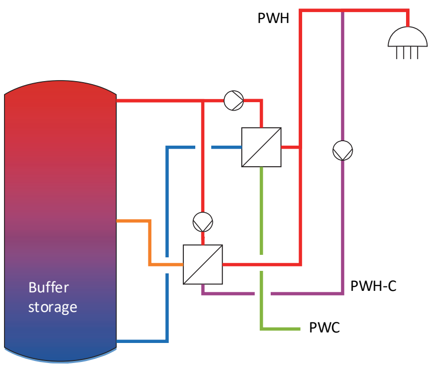
<tr>
<td>III Standard with circulation heat exchanger in parallel<br><br>Some products use a separate heat exchanger for circulation. With this parallel connection, the circulation heat exchanger and the associated pump can be optimised for the small volume flows. Switching time is below 2 s and UA-values are slightly higher than for II.<br>
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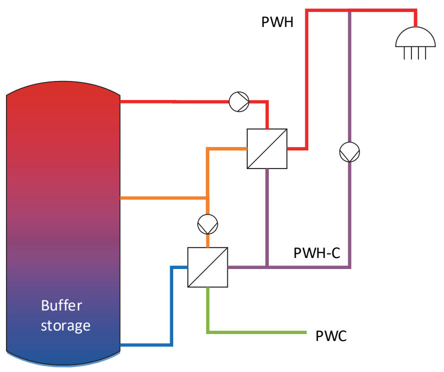
<td>IV Standard with circulation heat exchanger in series<br><br>Alternatively, it is conceivable to connect two heat exchangers in series. This enables particularly good cooling during tapping operation and highest UA-values. Switching time is also below 2 s.<br>
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The IWHs vary in switching time between circulation and tapping mode and the specific heat transfer rate, which is abbreviated as *UA* (note that this is not only a heat exchanger property, but rather a property of the IWH). They influence the three most important quality measures of IWH with regard to thermal energy efficiency, which are visualized in Fig. 4 using a module based on concept II. This generic IWH is used in TRNSYS to model all four types of modules.

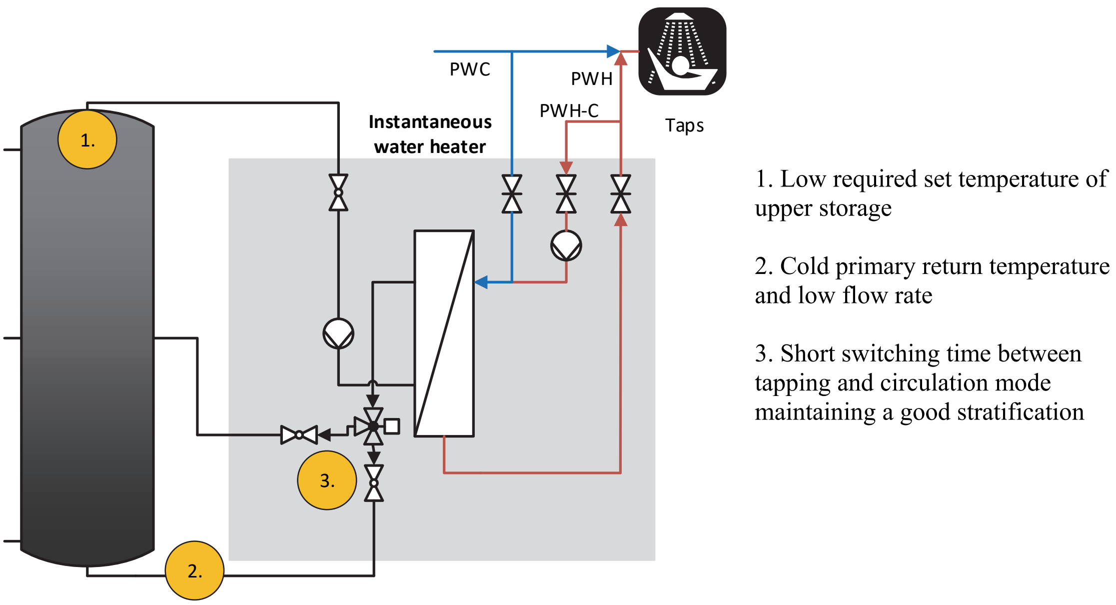


**Fig. 4: Generic instantaneous water heater model for simulating large DHW-systems with three quality measures**

A low required set temperature of the upper storage (**point 1**) to fulfill the demand is decisive for high solar fraction (or heat pump fraction) and low thermal losses. The required temperature difference between heating water inlet and domestic hot water outlet is not only a heat exchanger property, but also dependent from the whole module hydraulics.

Cold return temperatures on the primary side (**point 2**) improve the efficiency of all heat generators, including condensing boilers, and reduce temperature mixing in the storage by reducing the flow velocity at the tank connections.

In pure circulation mode (PWH-C), the secondary inlet temperature to the central IWH is 55 °C, so that the primary-side return flow is connected to the buffer tank in middle height to maintain temperature stratification. During tapping, the cold water temperature (PWC) dominates, so that the 3-way reversing valve switches the primary return flow to the lower storage tank section. A short actuating time (**point 3**) is essential to maintain the temperature stratification.

The specific heat transfer rates (*UA*-values) of the IWH modules are approximated and classified according to our laboratory measurements with following equations.

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

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

The temperature correction factor $f_\vartheta$ is only defined for primary inlet temperatures $\vartheta_{P,in}$ between 60 and 90 °C. The tapping flow rate on the secondary side $\dot{V}_{sec}$ is in l/min and the specific heat transfer rate (UA) is in W/K. Via the factor $f$ different powerful concepts of the IWH modules are simulated. $f$ is varied between 1.0 and 2.5.

Fig. 5 compares the variation range of the UA value according to eq. 2 with six different measured stations at 70 °C or 90 °C primary inlet temperature, 60 °C domestic hot water temperature and 10 °C cold water temperature. A factor $f$ = 1.0 to 1.5 represents a standard station for a small system according to concept I, whose performance is sufficient for the multi-family house tapping profile. Three different products Ia, Ib and Ic are shown here. The factor $f$ = 1.5 to 2.0 represents large modules for multi-family houses according to concept II or III. The factor $f$ = 2.5 stands for particularly efficient heat exchangers or concept IV with two heat exchangers connected in series. It is important to emphasize that the measured IWHs are only random samples and the following study is not a weighting of station concepts but of properties. Basically, each IWH module concept has the potential to achieve the same properties but at different costs.

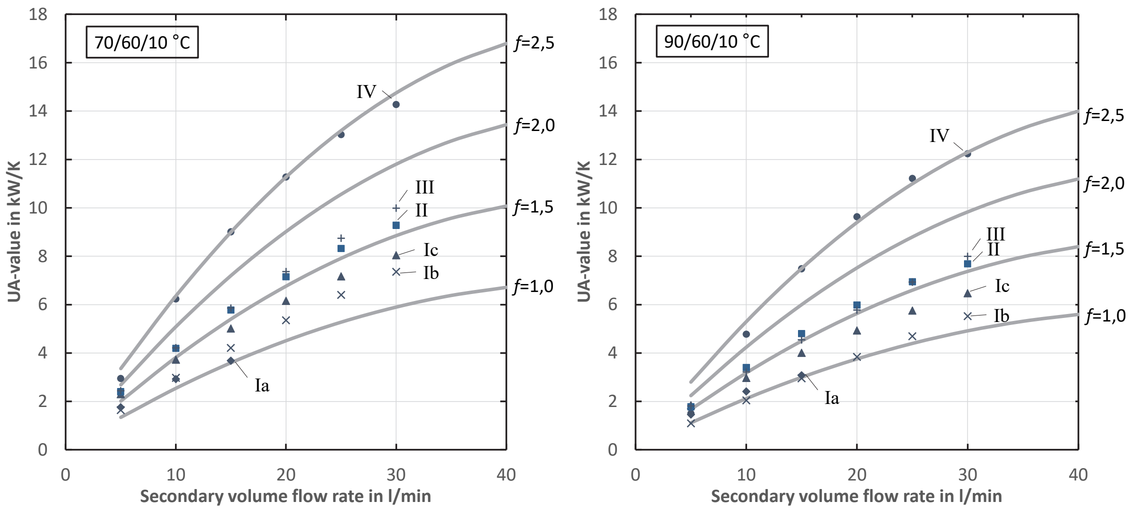


**Fig. 5: Comparison of different measured UA-values (points) of six different IWH at 70 °C/60 °C/10 °C (left) or 90/60/10 °C (right) with eq. 2 with different factors *f* (lines)**

The *UA* value in circulation mode or the *UA* value of the circulation heat exchanger is constant and set to 500 W/K due to the small volume flows and high temperatures.

The actuating time ($t_{RL}$) of the primary return between the lower and middle section of storage is modelled with Type 84 (moving average) between 2 s, 18 s, 34 s and 50 s. Table 3 shows the varied parameters. The set temperature of the gas boiler for the upper storage volume is part of a minimization search.

**Table 3: Overview of the varied parameters in the simulation**

| Factor *f* for UA | Changeover 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 | | |
| 2,0 | 34 s | | |
| 2,5 | 50 s | | |
| | Always bottom | | |

## 5. Results

As main evaluation parameter, the $CO_2$ savings (cf. eq. 4) are compared to a reference system, which is the standard IWH concept I without return diverter with a factor *f* of 1 of the *UA* value. To simplify matters, only the solar thermal system is switched off in the simulation. The tank size and connection heights of the gas boiler remain unchanged. The lower part of the storage tank heats up to 55 °C because of circulation mode. The set temperature in upper part is minimized with respect to DHW penalties, as well. It is 70 °C.

$$f_{sav,CO2} = 1 - \frac{\left(Q_{Gas} \cdot f_{Gas,CO2} + W_{el} \cdot f_{el,CO2}\right)}{\left(Q_{Gas} \cdot f_{Gas,CO2} + W_{el} \cdot f_{el,CO2}\right)_{ref}} \qquad \textbf{eq. 4}$$

The gas consumption $Q_{Gas}$ and the electricity consumption $W_{el}$ are multiplied with their corresponding emission factors. The $CO_2$ emission factors of the German electricity mix and natural gas change with the system boundaries (including or excluding upstream emissions) and time (especially for electricity). Taking into account upstream emissions and other greenhouse gases, according to a forecast of IINAS the emission factors for electricity in 2020 are $f_{el,CO2}$=403 gCO$_2$-eq/kWh$_{el}$ (Fritsche and Greß, 2019) and $f_{Gas,CO2}$=250 gCO$_2$-eq/kWh$_{Gas}$ for natural gas (Fritsche, 2016). As solar heat has a very low electricity consumption, we neglect its influence.

Comparing the bivalent system with the reference system (see Fig. 6 left), the $CO_2$ savings are highly dependent on IWH properties (35 to 46 %).

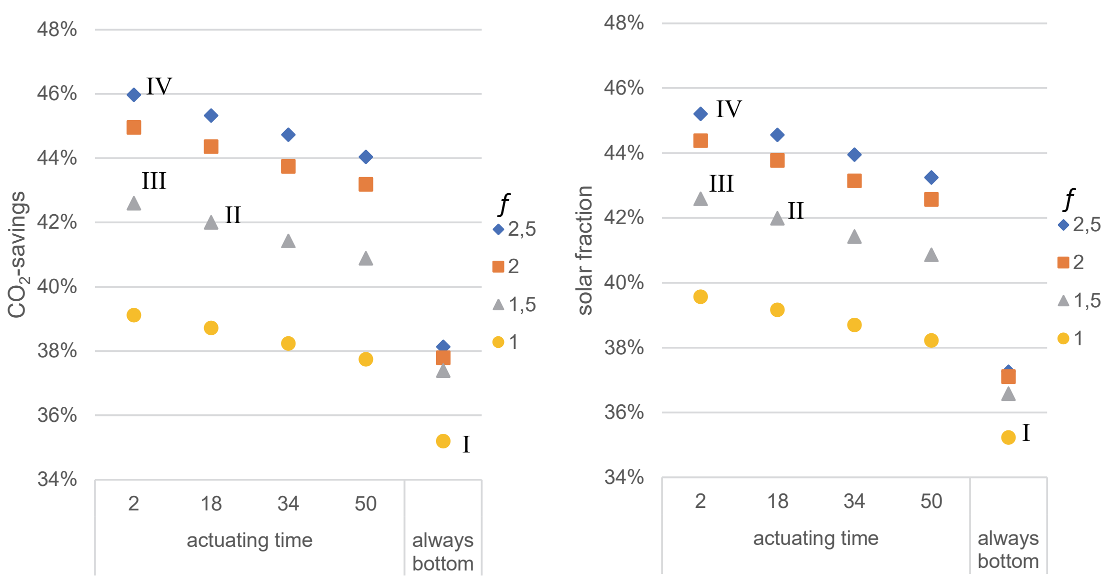


**Fig. 6: Influence of actuating time and specific heat capacity *UA* on $CO_2$ savings (left) and solar fraction (right) compared to the reference system (I, II, III and IV acc. to Table 2)**

The results clearly show that a switch between lower and middle storage section feed-in is beneficial in terms of $CO_2$-savings. A simple IWH designed for single family houses with always bottom storage feed-in (I) can supply the multi-family house without penalty, but achieves the lowest $CO_2$-savings of 35 %. Here, a higher specific heat transfer rate *UA* improves the results only by 3 %-abs. With return diverter the influence of the specific heat transfer rate (factor *f*) increases. Here, *f* improves the results by 6-7 %-points. Additionally, a fast return flow diversion, e. g. using two pumps or fast diverter valves, results in 4 %-abs better results compared to always bottom. Thus, the IWH concept IV reaches the highest $CO_2$-savings of 46 %. Note: when considering the fuel costs (not shown), this is exactly the same values.

To analyze the effects further, the solar fraction $f_{sol}$ is calculated as well according to eq. 5. Solar thermal heat $Q_{sol}$ and the heat from the condensing boiler $Q_{Boiler}$ are heat inputs to the storage. $f_{sol}$ is an indicator for low storage temperatures at the bottom part and for good stratification during discharging.

$$f_{sol} = \frac{Q_{sol}}{Q_{Boiler} + Q_{sol}} \qquad \textbf{eq. 5}$$

Fig. 6 (right) shows clearly, that the sensitivity of $CO_2$-savings with regards to the IWH properties comes mainly from the sensitivity of the solar fraction. All values are roughly 1 %-abs lower than the fractional $CO_2$-savings, which depends on the reduced storage and boiler losses. Thus, all the conclusions presented above are applicable to this figure. The solar fraction rises due to higher solar collector yields and lower upper set temperatures of the gas boiler.

These set temperatures, which have been minimized as explained above, are depicted in Fig. 7 over the factor *f* for the heat transfer rate. Note: Besides of stochastic fluctuations there is no significant influence of actuating time on minimum set temperature. However, efficient heat exchangers reduce the set temperature for the gas boiler of the upper storage by 5-6 K. The set temperature for the heater of upper storage part $T_{Set,HE} = 64.5\ °C$ for factor $f = 1$ can be significantly reduced down to 59 °C for concept IV.

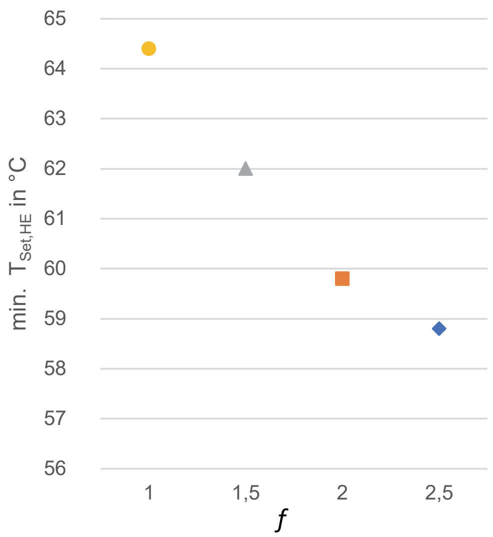


**Fig. 7: Influence of the factor *f* of the IWH on minimum set temperature of upper storage**

## 6. Summary

As the efficiency standard of buildings becomes more restrictive, the heating of domestic hot water is increasingly coming into focus, as it determines the minimum temperature level of the heat supply systems. Bivalent heat supply systems with IWH are a suitable means to decarbonize the heat demand in large domestic water installations. IWH are helpful because they create a cold preheating volume in the buffer storage tank, which enables the efficient integration of regenerative heat generators such as solar thermal systems and heat pumps.

In a parameter study, four different IWH concepts are investigated in an exemplary bivalent heat supply system with gas boiler and solar thermal collector for an apartment building. The specific heat transfer rate *UA* and the actuating time of the return flow diverter have a significant influence on the efficiency of the solar thermal system. The annual $CO_2$-savings increases from 35 % to over 46 % with higher *UA* and shorter actuating time of the return diverter. While a return flow diverter increases the solar yield and the $CO_2$-savings, it does hardly influence the minimum set temperature of the upper storage. To lower this temperature, a good specific heat transfer rate is beneficial.

However, if a two return system is available, it is advantageous if it is fast, so that the cold returns can be fed to the preheating section as quickly as possible. Hence, the transferability of the results to other bivalent heat supply systems with other operating strategies has to be investigated in more detail in future works.

## 7. Acknowledgement

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